EXAMINING SIMULATED DRIVING PERFORMANCE AMONG ATHLETES WITH A SPORT-RELATED CONCUSSION

By

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PUBLIC ABSTRACT

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Sport-related concussions (SRCs) can impact multiple domains, symptoms, neurocognitive and vestibular/ocular performances, which may affect concussed athletes with the ability to drive an automobile. However, limited research is available to assist clinicians on when concussed athletes should return to drive. **PURPOSE**: The first purpose of this study was to evaluate the reliability of the simulated driving software in a sample of healthy, college-aged students. The secondary purpose was to examine simulated driving performance in concussed athletes compared to non-concussed match controls, throughout the SRC recovery. Lastly, the third purpose of this study was to explore the relationship between simulated driving performance and concussions measures in concussed athletes, within 72 hours, asymptomatic and return to full participation sessions. **DESIGN**: Repeated-measures study. **INTERVENTION**: There was a total of 59 collegiate students who completed the test-retest reliability study of three driving scenarios, with one week in between two test sessions. Thirty-eight participants completed a series of SRC-based tools and driving simulation tests within 72 hours, when they become asymptomatic and when they return to full participation. Lastly, the tools that were utilized in the study were the Sport Concussion Assessment Tool (SCAT5), Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT), Balance Error Scoring System (BESS), Vestibular-Ocular Motor Screening (VOMS), and STISIM Drive® simulated driving tasks. **RESULTS**: The simulated driving software had poor to moderate reliability of their driving measures. There were no significant differences between concussed and non-concussed athletes in their simulated driving ability. However, nine concussed athletes collided with pedestrians and automobiles during the simulated driving scenarios. Lastly, we found numerous moderate to strong relationships between simulated driving performance and SRC tools. **CONCLUSIONS**: Driving in an impaired state may carry serious consequences that may affect both the concussed individual and others on the road. These results suggest that driving impairments may persist beyond when individuals with a concussion have returned to normal driving.

ABSTRACT

EXAMINING SIMULATED DRIVING PERFORMANCE AMONG ATHLETES WITH A SPORT-RELATED CONCUSSION

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Many healthcare professionals have incorporated a return to play and return to learn strategies within their sport-related concussion (SRC) management protocol but may not have considered the effects of driving performance, which is a common activity of daily living for most athletes. By having severe signs and symptoms, and impairments from a SRC, it could influence the way concussed drivers think and act throughout their recovery process. Therefore, this could impair their acceptable decisions and make it harder to detect and avoid hazards on the road. **PURPOSE**: The specific aim of this project was to evaluate the test-retest reliability of the STISIM Drive® simulated driving software in a sample of healthy, college-aged students. The secondary purpose was to examine simulated driving performance in concussed and non-concussed match control athletes within 72 hours of sustained SRC, asymptomatic and return to sport participation (RTP) sessions. Lastly, the third purpose of this study was to explore the relationship between simulated driving performance and concussion tests in concussed athletes, over their SRC recovery. **DESIGN**: Repeated-measures study. **INTERVENTION**: There was a total of 59 collegiate students, who completed the test-retest reliability of three driving scenarios, with one week in between two test sessions. A total of 38 concussed and non-concussed athletes completed a series of SRC-based tools and simulated driving tasks within 72 hours, when they become asymptomatic and when they return to full participation. Lastly, the tools that were utilized in the study were the Sport Concussion Assessment Tool (SCAT5), Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT), Balance Error Scoring System

(BESS), Vestibular-Ocular Motor Screening (VOMS), and STISIM Drive® simulated driving tasks. **RESULTS**: The STISIM Drive® software reflected poor to moderate reliability (0.25-0.86) for the STISIM Drive driving tasks. Within the memory, planning and navigation scenario, there were no group ($F_{1,28}$=1.56, p=0.73) or group X time ($F_{1,20}$=1.56, p=0.79) interaction main effects, however there was a time ($F_{1,20}$=1.56, p<0.001) main effect. Within the car following with divided attention (DA) scenario, there were no group ($F_{1,27}$=1.48, p=0.20) or group X time ($F_{1,18}$=1.09, p=0.43) interaction main effects, however there was a time ($F_{1,18}$=6.40, p<0.001) main effect. Within the passing, gap judging and merging scenario, there were no group ($F_{1,31}$=1.338, p=0.27), time ($F_{1,25}$=0.777, p=0.67), or group X time ($F_{1,18}$=1.09, p=0.43) interaction main effects, however there was a time ($F_{1,25}$=0.808, p=0.64) main effect. However, nine concussed athletes (47.4%) collided with pedestrians and automobiles during the simulated driving scenarios over their SRC recovery. Lastly, we found four strong relationships between simulated driving performance (i.e. turn signal usage, car collisions, speeding) and SRC tools (i.e. ImPACT, BESS, VOMS). **CONCLUSIONS**: These preliminary findings may guide clinicians, educators, and researchers in developing a comprehensive driving evaluation for concussed individuals, due to the numerous pedestrian and car collisions displayed by concussed athletes. These results suggest that driving impairments may persist beyond when concussed athletes are returning back to full participation in sport and school.

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CHAPTER 1

INTRODUCTION

1.1. Overview of the Problem

Sports play a unique and profound role in American society, with more than 200 million youth and adults participating in some form of sports.[1] Since there is a steady increase in sport participation among youth and adult populations, there is also an increase among sustaining injuries in sports. Between 1.6 and 3.8 million sport and recreation-related traumatic brain injuries (TBI) occur annually within the United States (US).[2] Current estimates show that 4.0 - 8.9% of all high school[3,4] and 4.0 - 7.9% of all collegiate athletic injuries[5-8] are sport-related concussions (SRC). With the growing concern of SRCs in physical activities, it has become a priority to educate athletes, coaches, parents, and the general public about the recognition and management of SRCs. Furthermore, advancements in the field of sports medicine has led to improved clinical practices for clinicians assessing and managing this injury.

A SRC is one of the most complex injuries to assess and manage in sports medicine. A SRC is defined as a trauma-induced alteration in mental status, induced by biomechanical forces and can be caused by either a direct blow to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head.[9,10] The effects of a SRC vary widely, depending on the severity of the injury, age, health, individual factors and recovery time. Furthermore, a suspected SRC can include one or more of the following clinical domains: 1) signs and symptoms, 2) physical signs, 3) balance impairment, 4) behavioral changes, 5) cognitive impairment and 6) sleep/wake disturbance.[9] Approximately 80 - 90% of these impairments from a SRC typically resolve within 7-10 days,[11,12] but some athletes remain symptomatic or impaired for weeks or months after a SRC.[13,14] Currently, healthcare professionals should immediately remove an athlete following a suspected SRC and the athlete should not be allowed to return to participation the same day of the injury.[9] Lastly, when assessing and managing a concussed athlete, clinicians should use a multifaceted approach and follow the graduated stepwise progression, when returning an athlete back to full participation in sport and school.[9,10]

Neurocognitive assessments have been described as an important 'cornerstone' of concussion management.[15] Given the pervasive nature of SRCs, and the wide variety of injury outcomes, the assessment of multiple aspects of cognitive function (e.g., executive function, attention, planning, memory, visuo-spatial, and cognitive flexibility) may provide additional insight into the persistent effects of concussive injuries.[16] In most concussion management programs today, computer-based neurocognitive batteries have largely replaced the traditional paper and pen neurocognitive tests.[17] Neurocognitive testing has been the gold standard in documenting deficits in cognitive function and is useful in detecting deficits following SRCs.[18] Although the neurocognitive evaluation is suggested to be the cornerstone of the evaluation, each facet of the multifaceted approach provides critical information to the clinician making a diagnosis and return to play decision in concussed athletes.[19]

Balance, spatial orientation and stable vision are important components of physical activity and athletic participation. The vestibular and ocular systems play a vital role in controlling each of these areas and can be negatively impacted by a SRC.[20,21] Vestibular function includes both sensory and motor systems and is involved in several different roles related to postural control or balance, including stabilization of the head, controlling the center of mass, sensing and perceiving motion and maintaining orientation to vertical.[22,23] After sustaining a SRC, the most common symptoms an athlete may face include headache, dizziness and balance problems.[24,25] Individuals who incur a SRC, 30% report balance dysfunction and 75.6% report dizziness as a debilitating symptom.[24,25] Two primary mechanisms have been proposed to underlie diminished vestibular function with concussion: 1) damage to peripheral receptors, or 2) inhibited sensory integration in response to structural damage of the central processing structures.[26] Currently, force plate technology is the gold standard for balance measurement for return to play, but with the expense it is often underutilized.[27]

Clinical recovery is defined as a return to normal activities of daily living, which include school, work and sport, after injury. In addition, it encompasses a resolution of post-concussion-related symptoms and a return to clinically normal balance and cognitive function. It is well established that SRCs can have large adverse effects on cognitive function and balance in the first 24–72 hours after injury.[9-11] Many concussed individuals recover within 10-14 days, with cognitive deficits, balance and symptoms improving rapidly during the first 2 weeks.[9] Driving is a component of independent functioning and an activity of daily living for many individuals, particularly where there is little access to public transportation. Moreover, driving a motorized vehicle involves individuals to have adequate emotional control, cognition, attention, and motor coordination.[28] Particularly for young and inexperienced drivers, operating a vehicle is a demanding cognitive task. Currently, teenagers are the greatest at-risk population for motor vehicle crashes within the U.S.[29] Additionally, the risk of motor vehicle collisions and death are higher among 16 - 19 year-olds than among any other age group in the U.S.[30] Furthermore, male drivers are two times more likely than female drivers (ages 16 - 19) to be killed in a car accident.[31] However, when considering driving performance, healthy males tend to take more risks, exhibit aggression and seek thrilling sensations compared to females.[32,33] Researchers have found that distractions, perception of hazard, sleep and passenger presence all affect adolescent drivers.[34,35]

While consensus documents[9,11] are available to guide return to sport and return to learn decisions, there is a distinct lack of evidence regarding return to activities of daily living that may expose concussed athletes to the risk of additional injury, such as driving. Driving impairments have been well documented in populations with more profound neurological disorders such as TBI,[36] Alzheimer's disease,[37,38] Parkinson's disease,[38,39] multiple sclerosis,[40] and various other neurological conditions. However, only two existing studies have examined individuals with a concussion, while performing a driving simulation task.[41,42] Schmidt and colleagues[41] suggest that concussed individuals presented with poorer simulated driving performance and 32% more lane excursions compared to controls when asymptomatic. While Schultheis et al.[42] suggested that changes in simulated driving performance are correlated with changes in cognitive performance. However, these studies were limited due to small sample size, short duration of testing, and lack of multiple concussion tools on simulated driving performance between concussed individuals. More importantly, these studies did not examine high school and collegiate athletes who are at a greatest risk for a motor vehicle accident. Despite these efforts, only 48% of individuals intend to reduce their driving at any point after sustaining a concussion.[43]

1.2. Significance of the Problem

Within the US, crash rates are the highest and most hazardous during the first six months of licensure without parental supervision.[44] Our society tends to view teens as young adults when, neurologically, they are not fully developed. In addition, adolescents differ significantly from adults, not only in size but also biomechanically, pathophysiologically, neurobehaviorally and developmentally.[45] Researchers suggest that the area of the brain that regulates logic and reasoning develops before the area that controls impulse and emotion.[46] Furthermore, studying risk taking within the context of driving is critical due to the public health threat posed by young drivers.[47] Research shows that parenting factors and individual difference variables, such as sensation seeking and risk perceptions, are associated with increased motor vehicle crash risk for young drivers.[47] Driving is a very complex activity of daily living, even in the best possible conditions for the driver. Driving consists of three main factors, which include cognition, vision, and motor function. Characteristics of the cognitive and motor function domains are attention, perceptual and visuo-spatial ability, speed and reaction time, memory and executive function.[48] Additionally, characteristics of the vision domain include eye health, visual acuity, visual fields, color vision, depth perception, field dependence, hearing and contrast sensitivity.[48] Since driving is a very dynamic task, similar impairments are seen in concussed athletes (i.e. cognitive, balance, vestibular/ocular).[9] Previous studies suggest that these measures are sensitive to driving impairments in patient populations with other neurological conditions (i.e. Alzheimer's disease, Parkinson's disease, and various other neurological conditions). By seeing these cognitive, vestibular/ocular motor impairments in other neurological conditions while driving, there is a gap in the literature regarding SRCs and simulated driving performance. Within the college-aged concussion literature, previous researchers found significant, positive correlations between neurocognitive testing and simulated driving performance.[41,42] In addition, only visual memory and processing speed significantly improved from the diagnosed concussion session to the return to full participation stage. Limitations of these studies include not evaluating the population that is at the highest risk of automobile accidents, high school and collegiate athletes, a short duration of testing, and a lack of a multifaceted approach. Thus, the presence of a SRC can compound these variables potentially leading to a further increase in the risk of a motor vehicle collision and endangering the lives of others on the road. Furthermore, it is crucial to incorporate a multifaceted approach in order to understand if there is a relationship between concussion management tools and simulated driving performance.

Return to drive following a SRC has recently become a focal point of the sports medicine community. However, very little research exists regarding post-concussion driving recommendations and guidelines. A recent study surveyed collegiate student-athletes regarding sustaining a concussion and driving practice immediately following. Results found three main themes: 1) despite generally believing that driving immediately following a concussion is unsafe, a majority of student-athletes did not refrain from driving at any point following their previous concussions, 2) the health care provider plays a critical role in post-concussion driving decisions, and 3) post-concussion driving restrictions may have some influence on student-athletes' decisions to report the injury to a health care provider.[49] This warrants an implementation of a return to drive protocol for healthcare providers, since return to drive is not a trademark or a critical component of the return to sport guidelines in concussed athletes. Additionally, researchers need to investigate different time points of the recovery process, in order to provide healthcare professionals appropriate guidelines throughout the management of a concussed athlete.

The process of recovery and return to sport participation after a SRC, follows a graduated stepwise rehabilitation strategy.[9] When using a multi-faceted, comprehensive management approach, the recovery time for a SRC may take up to four weeks, dependent upon the various domains of impairments of a concussed individual.[50] The literature documenting the time to symptom resolution is disparate; some studies report alleviation within 5 to 10 days,[51-53] whereas others have documented post-concussion symptoms beyond 7 to 14 days.[54,55] Researchers have reported that balance impairment resolves within 7 days of SRCs in 90% of cases.[56] Lastly, vestibular and ocular motor impairments have been linked to worse outcomes after a SRC,[57] with decrements resolving between 1 and 3 weeks after a SRC.[50] Since the recovery stages of a SRC is within 4 weeks typically, this is the most likely the time concussed athletes would return to driving and could show differences compared to non-concussed athletes during the acute and subacute stages. Therefore, there may be differences seen within the acute and subacute stages of a concussed athletes' recovery process and simulated driving performance, while their simulated driving performance and deficits from the SRC should return to "normal" during the return to full participation stage.

As high school and college sport participation continues to rise in the US, healthcare professionals must find a way to provide the best possible care for their athletes. Many sports medicine clinicians have incorporated return to play and return to learn strategies within their concussion management protocol but may not have considered the effects of driving performance, which is a common activity of daily living for most athletes. By having severe signs and symptoms from a SRC and behavioral impairments, it could influence the way concussed drivers think and act throughout their recovery process. Additionally, this could impair their acceptable decisions and make it harder to detect and avoid hazards on the road. Therefore, it is vital to examine simulated driving performance among high school and collegiate athletes with a SRC. By doing so, this study will provide clinicians with various clinical indicators of recovery points (i.e., 72 hours, when asymptomatic and return to full participation) during the SRC recovery phase. Additionally, this study is vital for healthcare providers in determining recommendations and guidelines for a safe return to drive, if there are poorer simulated driving performance in concussed athletes.

1.3. Purpose of the Study

The aims of this study were to evaluate the test-retest reliability of the Systems Technology Incorporated Simulation (STISIM) Drive® software, examine simulated driving performance between concussed and non-concussed high school and collegiate athletes, and explore the relationship between simulated driving performance and common concussion measures (i.e. symptoms, neurocognition, balance and vestibular/ocular motor) across concussion recovery. More specifically, the primary purpose was to evaluate the test-retest reliability of the STISIM Drive® software in a sample of healthy, collegiate students, with one week in between sessions. The secondary purpose was to examine simulated driving performance (i.e. road lane excursions, centerline crossings, car collisions, pedestrian collisions, stop sign tickets, speeding tickets, turn signal usage and divided attention (DA)) between concussed high school and collegiate athletes and matched non-concussed high school and collegiate athletes within 72 hours, asymptomatic and return to full participation. The tertiary purpose was to explore the relationship between simulated driving performance and concussion measures (i.e. symptoms, neurocognitive, balance, and vestibular/ocular motor measures) in concussed athletes within 72 hours, asymptomatic and return to full participation.

1.4. Hypotheses

Aim 1: To evaluate the test-retest reliability of the STISIM Drive® software (i.e. all three scenarios) in healthy, college aged students, with one week in between each session.

H1a. The STISIM Drive® software will reflect acceptable ICC values (0.75).

Aim 2: To compare simulated driving performance (i.e. road lane excursions, centerline crossings, car collisions, pedestrian collisions, stop sign tickets, speeding tickets, turn signal usage and DA) between concussed high school and collegiate athletes and matched non-concussed high school and collegiate athletes over the clinical indicators of the SRC recovery (i.e. within 72 hours, asymptomatic, return to participation).

H2a: Concussed high school and collegiate athletes will perform more road lane excursions, centerline crossings, car collisions, pedestrian collisions, speeding tickets, stop sign tickets, and have less turn signal usage and DA on the simulated driving tasks within 72 hours and asymptomatic stages, compared to matched non-concussed high school and collegiate athletes.

H2b: There will be no differences on road lane excursions, centerline crossings, car collisions, pedestrian collisions, stop sign tickets, speeding tickets, turn signal usage and DA on the simulated driving tasks at the return to full participation session between concussed and matched non-concussed high school and collegiate athletes.

Aim 3: To examine the relationship between simulated driving performance measures and concussion measures (i.e. symptoms, neurocognitive, balance, and vestibular/ocular motor) in concussed athletes over the clinical indicators of the SRC recovery (i.e. within 72 hours, asymptomatic, return to participation).

H3: There will be a strong association between simulated driving performance measures and concussion measures (i.e. symptoms, neurocognitive, balance and vestibular/ocular motor) at all clinical indicators of the SRC recovery (i.e. within 72 hours, asymptomatic, return to participation) for the concussed group.

1.5. Operational Definition of Terms

Sport-Related Concussion: A traumatic brain injury induced by biomechanical forces and may be caused either by a direct blow to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head.

Neurocognitive Performance: Scores on a battery of scientifically-validated computerized tests that measure verbal memory, visual memory, visual motor speed, impulse control, and reaction time.

Balance Performance: Error scores were recorded on the Balance Examination Scoring System (BESS), through three different stances on a firm and foam surface, while participants were instructed to stand quietly with their eyes closed and their hands on their iliac crests, in each stance for 20 seconds.

Vestibular Ocular Motor Performance: A screening tool to assess vestibular and ocular motor impairment through participant-reported symptom provocation following each assessment. The five sections of the screening include: 1) smooth pursuits; 2) horizontal and vertical saccades; 3) convergence; 4) horizontal and vertical vestibular ocular reflex (VOR); and 5) visual motion sensitivity (VMS).

Simulated Driving Performance: A simulated driving software that utilizes three driving scenarios: 1) memory, planning, and navigation, 2) car following with DA, 3) passing, gap judging and merging.

Speeding Tickets: Total number of instances where the vehicle exceeded the speed limit and the police was called to the scene (generally providing auditory feedback).

Stop Sign Tickets: Total number of instances where the driver's vehicle did not come to a complete stop within 2 car lengths of the stop sign.

Car Collisions: Total number of instances where the driver's vehicle contacted, either another vehicle, a barrel, a barrier or a collision block.

Pedestrians Collisions: Total number of instances where the driver's vehicle touched a pedestrian model.

Road Edge Excursions: Total number of times where any portion of the driver's vehicle left their defined roadway lane and entered the shoulder.

Centerline Crossing: Total number of times where any portion of the driver's vehicle left their defined roadway lane and crossed over the double-lined on on-coming traffic.

Turn Signal Usage: Based on three criteria: 1) good performance, 2) poor performance and 3) missed signal. Good performance was defined as instances where the driver correctly signaled for a turn or lane change well in advance of the required action and left the turn signal on until the action was completed. Poor performance was defined as instances where the driver used the turn signal but did not provide adequate warning to other drivers or did not maintain the use of the turn signal through the entire maneuver. Missed signal usage was defined as instances where the driver negotiated a turn or lane change without the use of their turn signals.

Over Speed Limit Percentage: Percentage of driving time and distance the driver spent above the specified speed limits.

Divided Attention (DA) Response: Symbols are displayed on the screen and the driver must respond by tapping a button on the steering wheel that corresponds with the symbol. Responses were displayed by three criteria: 1) 0 = correct, 2) 1 = incorrect, 3) 2 = missed.

DA Total Response Time: The average response time of all 23 DA tasks that were given in the DA driving scenario.

Pedestrian Collision Response Time: The average response time of three DA responses relating to the three pedestrian models walking in front of the driver's vehicle unexpectedly.

Car Collision Response Time: The average response time of three DA responses relating to the three cars pulling out in front of the driver's vehicle unexpectedly.

CHAPTER 2

REVIEW OF THE LITERATURE

This review of the literature provides a comprehensive summary of the research on SRCs, particularly in high school and collegiate athletes, as well as the effects of simulated driving performance in concussed athletes. The three main components of the literature review include the background and epidemiology of SRCs, the assessment and management of SRCs, and driving. This first part of this review defines a SRC and the pathophysiology, epidemiology risk factors and sex considerations regarding SRCs. This is followed by an overview of the advancements in the assessment and management of SRCs with separate sections dedicated to symptoms, neurocognitive and postural stability. Additionally, the return to full participation, return to learn and return to drive will be discussed in the recovery of a SRC. The remaining portion of this review discusses the driving aspects including car collision rates, at-risk populations and the use of car simulators. This chapter concludes with a summary of the relevant gaps in the literature and the purposes of the present study.

2.1. Background of Sport-Related Concussions

2.1.1. Definition of a Sport-Related Concussion

Concussion is derived from the Latin concutere, meaning "to shake violently". The definition of a concussion has been highly debated and has evolved over the past several decades due to the increasing knowledge within research and media coverage. Furthermore, since there is no universal agreement[58] on the definition of a concussion, it has been proposed that the term should not be used interchangeably with mild traumatic brain injury (mTBI) or post-concussion syndrome, since these injuries are separate entities, have vague definition, not based on validated criteria, and may have longer-term neuropsychological sequelae.[9,11,59]

Currently, the National Athletic Trainers' Association (NATA) position statement for managing SRCs and the American Academy of Neurology (AAN) utilize the same definition of a concussion, which states is a "trauma-induced alteration in mental status that may involve loss of consciousness.[10,60] A more well-defined and accepted definition within sports medicine was established from the 5th Consensus Statement on Concussion in Sport. The expert panel defined concussion as a "traumatic brain injury induced by biomechanical forces". Several common features that may be used in clinically defining the nature of a concussive head injury include: 1) SRCs may be caused either by a direct blow to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head, 2) SRCs typically results in the rapid onset of short-lived impairment of neurological function that resolves spontaneously. However, in some cases, signs and symptoms evolve over a few minutes to hours, 3) SRCs may result in neuropathological changes, but the acute clinical signs and symptoms largely reflect a functional disturbance rather than a structural injury and, as such, no abnormality is seen on standard structural neuroimaging studies, and 4) SRCs result in a range of clinical signs and symptoms that may or may not involve loss of consciousness. Resolution of the clinical and cognitive features typically follows a sequential course. However, in some cases symptoms may be prolonged.[9]

2.1.2. Pathophysiology of a Sport-Related Concussion

SRCs are described as functional injuries instead of structural injuries. This stance is rooted in the frequent presentation of symptoms and cognitive deficits reported by concussed athletes with grossly normal structural neuroimaging (e.g. computed tomography and magnetic resonance imaging). Moreover, these biomechanical forces result in abnormal function at the level of the individual cell. Thus, concussions may be a result of neuropathological changes such as microstructural and even eventually macrostructural damage.[61] Computed tomography and magnetic resonance imaging add little to the concussion-evaluation process, but should be employed whenever suspicion of an intracerebral or structural lesion (e.g. skull fracture) exists.[11] Although other diagnostic techniques, such as functional magnetic resonance imaging,[62] diffusion tensor imaging, magnetic resonance spectroscopy,[63,64] serum biomarkers,[65] and biomechanical techniques,[66,67] may be helpful in identifying and diagnosing concussion, their exclusive use as diagnostic tools have not been validated.[10]

When direct or indirect linear and/or rotational forces are applied to the brain,[59,68] the underlying neural elements are exposed to a shearing strain.[69] Following this shearing strain, there is an alteration to normal brain function, termed 'neurometabolic cascade.' Immediately after sustaining a SRC, indiscriminate release of neurotransmitters and unchecked ionic fluxes occur.[70] The binding of excitatory transmitters, such as glutamate to the N-methyl-D-aspartate (NMDA) receptor, leads to further neuronal depolarization with efflux of potassium and influx of calcium.[70] This ionic shift leads to acute and subacute changes in cellular physiology. During this time, the mitochondria struggles to meet the cellular demands of ATP production.[71] Without ATP, the ATP-dependent sodium-potassium pump will fail to maintain ionic homeostasis.[61] The metabolic mismatch and specifically the increased energy demands activate glycolysis, which produces lactic acid.[61] Accumulation of lactic acid will break down the blood–brain barrier and can result in massive cerebral edema.[72] To reestablish the neuronal member potential acutely, the sodium potassium pump works strenuously. The sodium potassium pump requires a dramatic jump in glucose metabolism. This stage of "hypermetabolism" occurs in the setting of diminished cerebral blood flow and the disparity between glucose supply and demand triggers a cellular energy crisis. Functional MRI has demonstrated that cerebral blood flow changes correlate with initial symptom severity, but may return to baseline or normative ranges slower than subjective symptom reporting and neurocognitive testing.[73,74] This suggests that cerebral blood flow changes likely persists even after symptoms and signs have resolved.[61] Following the initial period of accelerated glucose utilization, the brain goes into a period of depressed metabolism. Persistent increases in calcium may impair mitochondrial oxidative metabolism and worsen the energy crisis. Unchecked calcium accumulation can also directly activate pathways leading to cell death. Intra-axonal calcium flux had been shown to disrupt neurofilaments and microtubules, impairing post-traumatic neural connectivity.

A majority of athletes will recover completely after sustaining a SRC, however a minority will suffer persistent symptoms and possibly neurodegenerative changes, due to a persistent and sustained neuroinflammatory response.[61] Studies have demonstrated that white matter tract disruption and persistent microglial activation after repetitive mild traumatic brain injury may result in permanent changes.[70,75,76] Furthermore, the physiologic basis for concussion and post-concussive symptoms has its origins in both experimental animal and human work following a concussive injury and show a vulnerable period to repeat injury exists.[77]

2.1.3. Epidemiology of Sport-Related Concussions

Participation in sports and recreational activities is an important part of the American culture in youth and adult populations. Along with the associated benefits of participation in sports and physical activity, comes the risk of injury. Because of the high level of uncertainty surrounding brain injuries, SRCs are a cause of growing attention and continues to be a serious public health concern. In addition, approximately 1.6 to 3.8 million concussions occur annually within the U.S.[2] Of those concussions, an estimated 300,000 are SRCs, which account for approximately 4-9% of all sport injuries.[3,25,78-80] However, this number may be underestimated, as many concussed individuals fail to seek medical care or hide their injury.[5] Considering these statistics, along with the increased rates in sport participation, it is expected that the annual incidence of SRCs will continue to rise relative to these increases in sport participation.[81]

The media and research's focus on SRCs has mainly surrounded collegiate and professional athletes, yet nearly 8 million high school athletes make up the single largest athletic cohort in the country annually.[82] The daily sport activities, physical demands, potential for physical contact, and repetitive stress associated with sports activities, place young athletes at risk for injury. Moreover, there is a recent interest in high school athletes and their risk for sustaining SRCs, as well as the long-term consequences resulting from SRCs. Due to the small proportions of high school athletes continuing to play at the collegiate and professional levels,[83] it is important to examine the health and safety of this young population alongside their older counterparts.

Injury Rates in High School Sports

SRCs occur across a wide variety of high school sports and represent approximately 4-9% of all high school athletic injuries.[3,4] In 2007, Gessel and colleagues[4] examined concussion injury rates among high school and collegiate athletes through the High School Reporting Information Online (RIO) system. A total of nine high school sports were studied throughout the 2005-2006 academic year, with 8.9% of all injuries reported representing SRCs.[4] The injury rate was 0.23 SRCs per 1000 athlete-exposures (AE).[4] A recent study examined the academic years from 2005-2006 through 2011-2012, in nine high school sports. SRC rates appeared to increase beginning in 2008-2009 through 2011-2012, with the overall rate of SRCs increasing significantly from 0.23 to 0.51.[79] Five of nine sports indicated a significant increase in SRC rates over time, including football, boys' basketball, boys wrestling, boys' baseball, and girls' softball, while the other four sports shown increasing trends but did not reach significance.[79] In contrast, Lincoln et al.[80] reported a significant increase in SRC rates for 12 high school sports in a single school district, over an 11-year period (1997-1998 through 2007-2008). This raises the question of whether SRC rates were rising nationally during the same 11-year period, in which Rosenthal et al.[79] only saw an increase in SRC rates between the years of 2008-2012. Results among the 12 sports revealed that football accounted for more than half of all SRCs, with boys' lacrosse with the second largest incidence.[80] Among girls' sports, soccer had the highest incidence of SRCs, followed by cheerleading and basketball.[80] The overall SRC rate across all 12 sports increased over the 11-year period from 0.12 to 0.49 per 1000 AEs.[80]

O'Conner et al.[3] described the epidemiology of SRCs in 27 high school sports for the 2011-2012 through 2013-2014 academic years. Overall, SRCs were reported at a rate of 3.89 per 10,000 AEs.[3] Football had the highest SRC rate (9.21 AEs), followed by boys' lacrosse (6.65 AEs) and girls' soccer (6.11 AEs).[3] Similarity, Marar et al.[25] found football to have the highest injury rate at 6.4 SRCs per 10,000 AEs, followed by girls' soccer (3.4 AEs), and boys' wrestling (2.2 AEs).[25] Lastly, they furthered examined recurrent SRCs and found 11.5% of all concussed high school athletes had a recurrent SRC, with almost 20% and 18.5% of recurrent SRCs sustained in boys wrestling and boys' track and field, respectively. Similarly to Marar and colleagues,[25] the epidemiology of recurrent and new SRCs were examined by Castile and colleagues,[84] out of concern for the potential of long-term and traumatic effects associated with a SRC. From 2005-2010, a total of 2417 SRCs were reported, with 2110 new and 292 were recurrent SRCs.[84] The rate of new SRCs were 22.2 per 100,000 AEs, while the rate of recurrent SRCs were 3.1 per 100,000 AEs.[84] Football had the highest number of new SRCs, followed by girls' soccer, boys' soccer, and girls' basketball.[84] In contrast to Marar et al.[25] results with the highest recurrent SRCs seen in wrestling and boys' track and field, recurrent SRCs were highest in football (6.3 per 100,000 AEs), followed by girls' soccer (4.1), and girls' basketball (2.9).[84]

Schallmo and colleagues,[85] also conducted a study over a 9-year span (2005-2014) and aimed to track sex and sport-specific trends among SRCs in high school athletes through the High School RIO system. Between the 2005-2006 through 2014-2015 academic years, the SRC injury rate was 3.46 per 10,000 AEs. Based on the injury proportion ratio, SRCs were more common in girls' soccer (34.5%) than in any other sport, which is in contrast to the previously aforementioned studies that reported football.[85] Possible reasons for the rise in SRC risk in girls' soccer compared with boys' football include the lack of protective gear, emphasis on in-game contact, and potential increase in headers during game play.[85]

Injury Rates in Collegiate Sports

As mentioned previously, SRCs are a significant public health epidemic among collegiate athletes and research is limited in regard to the incidence of SRCs in the collegiate setting. Football players face the highest rates and greatest total number of SRCs of any collegiate contact sport[25] and comprise up to 55% of all collegiate sports SRCs.[8] Additionally, current estimates show that 4.0 - 7.9%[5-8] of all collegiate athletic injuries are SRCs. Moreover, Daneshvar et al.[5] summarized the data from the National Collegiate Athletic Association (NCAA) Injury Surveillance System (ISS) and found that from the 1988-1989 through 2003-2004 seasons, the SRC rate doubled from 0.17 to 0.34 of 1000 AEs.

Only two studies[86,87] have examined SRC incidence in collegiate football players alone. From 1999-2001, a total of 2905 football players were tested at preseason baseline and were followed up prospectively to ascertain SRC occurrence and for repeat SRCs, until completion of their collegiate football career.[86] With only 94 SRCs sustained, the overall rate of incident SRC was .81 per 1000 AEs.[86] Additionally, 35.1% of the concussed individuals had repeat injuries within the last seven years.[86] Lastly, players who reported a history of three or more previous SRCs, were three times more likely to have an incident SRC than players with no SRC history.[86] In contrast to the study of Guskiewicz et al.,[86] two recent studies[6,88] examined the epidemiology of SRCs in 25 NCAA sports, instead of the sport of football alone. Both studies had the exact same injury rate of 4.47 per 10,000 AEs, with the largest SRCs occurring in football, men's ice hockey, and women's soccer.[6,88] Additionally, both studies found 9.0% of the sustained SRCs to be recurrent.[6,88] Lastly, a similar study examined six NCAA sports, and found the SRC incidence to be slightly higher with a rate of 5.47 per 10000 AEs.[89]

In comparing high school and collegiate injury rates, Gessel et al.[4] determined that there was a higher rate of SRCs in collegiate sports (0.43 concussions per 1000 AEs) than high school sports (0.23 concussions per 1000 AEs). This is contrary to the findings of the study conducted by Guskiewicz and colleagues,[90] who reported a greater injury rate of SRCs for high school football athletes compared to collegiate football athletes. Reasons for the higher rates of SRCs at the high school level was attributed to a higher percentage of high school players being exposed to contact compared to players on a division I team and high school players play both offensive and defensive positions, which accounts for more tackling and contact during practices and games, which in returns increases their total exposure.[90] It is important to note that Gessel and colleagues[4] did conclude that SRCs consisted of a greater quantity of total injuries sustained by high school athletes than by collegiate athletes in all sports except volleyball and men's basketball.

Competition vs. Practice Injury Rates among High School and Collegiate Athletes

A majority of epidemiology studies state that SRCs are higher in competitions rather than in practices.[3,4,25,78,84] More specifically, rates ranged from .53-.87 for competitions and .11-.26 for practices, with SRCs occurring more in competitions.[3,4,25] However, many studies differed based on increased rates of SRCs in practices compared to competitions in a variety of sports. Gessel et al.[4] found that out of the nine high school sports, seven sports had a higher rate of SRCs in competitions compared to practices, with the exception of girls' softball and volleyball. In contrast, O'Conner et al.[3] found that most high school sports had significantly higher SRC rates in competitions than in practices, except for boys' baseball and tennis and girls' gymnastics, swimming and diving, and indoor and outdoor track and field. Furthermore, Marar et al.[25] found the rate of SRCs higher in competition than in practice for all high school sports, except cheerleading. In addition, with regards to recurrent SRCs, competitions remained higher than practices of incurred SRCs, except for volleyball and softball.[84] Moreover, boys' soccer had the highest risk of recurrent SRCs in competitions compared to practices, followed by girls soccer.[84]

There is limited research that has examined the SRC injury rates among competitions and practices in the collegiate setting. Results are similar to the high school SRC injury rates, in which SRCs are sustained higher in competitions than in practices.[6,86,88,89,91] More specifically, two studies examined the SRC injury rates in NCAA football players only.[86,91] Both studies stated SRCs were sustained higher in competitions than practices and had similar injury rates (i.e. 3.81 vs. 4.46 competitions and .47 vs. .92 practices) per 1000 AEs.[86,91] In addition, Houck et al.[91] found the number of SRCs in competitions were highest for special teams, followed by linebackers and wide receivers, while in practices SRCs rates were highest in offensive line, followed by wide receivers, and special teams.

Within recent years, there was a need to for updated incidence information, specifically examining all sports instead of the sport of football alone. Two studies reported over a five-year period, examining the SRC rates in NCAA sports, and found injury rates were higher in competitions than practices.[6,89] Zuckerman et al.[6] reported 12.81 per 10,000 AEs in competitions, with 2.57 per 10,000 AEs occurring in practices, in all sports except men's indoor and outdoor track, women's outdoor track and women's cross-country. This was similar to Wasserman et al.[88] with the competition injury rate at 14.59 per 10,000 AEs and practice rate at 2.57 per 10,000 AEs. Similarly, Covassin et al.[89] found higher SRC rates in competitions than practices and was seen in all sports. Furthermore, they found the highest SRC injury rates in men's ice hockey, followed by men's lacrosse, and women's soccer in competitions and the highest SRC injury rates in women's basketball, women's ice hockey and women's soccer in practices.[89] In contrast, Zuckerman et al.[6] found the highest SRC rates in men's wrestling, football and men's ice hockey in competitions and the highest SRC rates in men's wrestling, football and women's basketball in practices. However, it is important to note, that these studies did not examine the same sports, which explains the differences shown above.[6,89]

SRC Injury Rates among High School and Collegiate Athletes in Sex-Comparable Sports

Epidemiological data gathered at the high school level suggest that sex differences exist in SRC rates. More specifically, girls sustain more SRCs than boys in sex-comparable sports (i.e. soccer, baseball/softball, track & field, swim and dive, basketball).[3,4,25,79,80,85] A few studies have suggested that girls are at a 1.5 to 2 times greater risk than boys when incurring a SRC at the high school level.[3,25,80] Furthermore, recurrent SRCs within sex-comparable sports, with the exception of track and field and swimming and diving, girls have a greater percentage of recurrent SRCs compared to their male counterparts.[25]

Only two studies have investigated SRC injury rates among collegiate athletes in sex-comparable sports.[6,89] Both studies suggest that females are at a greater risk of sustaining a SRC in most sex-comparable sports compared to males. Zuckerman et al.[6] reported sex differences in four out of five sex-comparable sports. Specifically, women's soccer, basketball, lacrosse, and softball all reported higher overall SRC rates compared with their male counterparts, with the exception of ice hockey.[6] Similarly, Covassin and colleagues[89] examined sex-comparable sports and found females had a 1.4 times higher overall SRC rate than males, with greater rates in women's baseball/softball, basketball, ice hockey and soccer. However, the only sport in which males had a higher SRC injury rate than females was lacrosse, with a 1.1 times greater risk for incurring a SRC in either practice or competition.[89] In contrast, female softball players had almost a 2 times greater risk compared with male baseball, female soccer players had a 1.54 times greater risk compared with male soccer players, female basketball players had a 1.4 times greater risk compared with male basketball players and female ice hockey players had a 1.1 times greater risk compared with male ice hockey players.[89]

Mechanisms of SRCs among High School and Collegiate Athletes

Epidemiological studies have also investigated SRC injury patterns by sport in terms of mechanisms. The most common mechanism of a SRC injury was player-to-player contact.[25,84,92] More specifically, Marar et al.[25] found the most common mechanism of SRCs, across 20 high school sports, were player-player contact (70.3%) and player-to-playing surface contact (17.2%). Similarly, Meeham et al.[92] found the most common injury mechanism was player-to-player contact (76.2%), followed by contact with the playing surface (15.5%) and contact with a playing apparatus (7.7%). The most common type of high school player-to-player contact was head-to-head collisions (52.7%), followed by 38.9% resulted from collisions between the head of the injured athlete and a different body part of another player, and lastly 8.4% resulted from the injured athlete's head striking the playing surface secondary to player-to-player contact. Castile et al.[84] furthered examined new and recurrent SRCs mechanisms, which resulted in the highest from contact with another person (73.4% and 77.9%, respectively). In sex-comparable sports, boys had a higher proportion of sustaining SRCs from player-to-player contact (73.4%) than girls (55.6%), however, this sex difference held true for new SRCs, but did not for recurrent SRCs.[84] Conversely, girls had a higher proportion of SRCs from contact with the playing surface (25.3%) than boys (16.4%), however, this difference held true for new SRCs, but did not for recurrent SRCs.[84]

Lastly, only two studies have examined mechanisms of sustained SRCs in the collegiate setting and aligns with mechanisms of SRCs in the high school setting.[6,86] The most common mechanism was player-to-player contact. Guskiewicz and colleagues[86] utilized a prospective cohort study to examine mechanisms of SRCs sustained by NCAA football players. They found the most common SRC mechanisms were collision with an opponent (37.8%), tackling an opponent (21.4%) being tackled by an opponent (16.8%) and blocking an opponent (14.8%).[86] Likewise, Zuckerman et al.[6] found the most common mechanism of injury, across 25 sports, to be player-to-player contact, however the injury mechanism–activity combinations varied by sport.

Estimating the true prevalence and incidence rates for SRCs is a challenging task, specifically due to study designs (retrospective vs. prospective), differences between sample populations (i.e. age groups, rules), differences in calculating injuries rates (i.e. AEs) and different definitions of SRCs across the years. Furthermore, a number of SRC epidemiology trends occurred across multiple studies in regard to incidence, mechanisms, sex-comparable sports, and symptoms. First, the incidence of SRCs was ranked highest in football, ice hockey, women's soccer, boys' lacrosse and women's basketball.[3,6,25,79,80,84,85,88,90] Second, the injury rates and the likelihood of a SRC occurring was found to be highest in competition than practices.[4,6,25,78,84,88,90] Third, the most common mechanism for sustaining a SRC was player to player contact.[3,6,25,78,84,90,92] Fourth, females sustain a higher number of SRCs compared to males in sex-comparable sports.[4,25,79,80] Future studies regarding epidemiology of SRCs should continue to improve the efforts of defining what a SRC is and become more accurate in determining the prevalence and incidence of SRCs, while using more precise methodical practices.

2.1.4. Sex Considerations in Sport-Related Concussions

Student-athletes that compete at the high school and collegiate levels, are at an all-time high with sport participation. Within the National Federation of State High School Associations, nearly eight million high school athletes participated in athletics during the 2017-2018 academic years.[93] Moreover, almost 500,000 athletes competed in the NCAA within the 2017-2018 academic years, with an increase of more than 3,000 since 2016-2017.[94] Furthermore, girls' and women's sport participation has increased steadily at both the high school and collegiate levels, throughout the 20th century.[93,95] The steady increase in male and female sport participation at both the high school and collegiate levels, have prompted researchers to investigate sex differences in SRCs and related outcomes.

2.1.4.1. Symptoms

Healthcare professionals depend on self-reported symptoms and remains an area of importance in the management of concussed individuals. However, researchers suggest athletes may hide or minimize their symptoms for a variety of reasons, such as feelings of guilt from letting their team down, did not want to see a physician, did not think it was serious enough to warrant medical attention or did not want to lose playing time.[96,97] The majority of research suggest that concussed female athletes report more SRCs symptoms and take longer to become asymptomatic than concussed male athletes.[98-104] Furthermore, a recent study found the average symptoms recovery time for females was 75 days, compared to males who took an average of 49 days to recover from their SRC.[105] Sex differences have been examined in the type of symptom, following a SRC. Males are more likely to report amnesia and confusion/disorientation as a primary symptom, yet females report more drowsiness and sensitivity to light following a SRC.[106,107] Moreover, females significantly rate headache, pressure in head, feeling slowed down, difficulty concentrating, feeling more emotional, irritability, and sadness higher than males.[99] When examining symptoms that are grouped into clusters, concussed females present a greater number of symptoms in the somatic, migraine, cognitive, fatigue, and emotional clusters compared to concussed males.[98,108-110]

2.1.4.2. Neurocognition

In addition to sex differences in symptoms, researchers have also investigated differences between male and female athletes in neurocognitive function following a SRC. A majority of researchers suggest that female athletes have greater neurocognitive impairments in reaction time and visual memory, when compared to male concussed athletes.[98,111-113] Additionally, concussed females are cognitively impaired 1.7 times greater than concussed males.[114] In contrast, other researchers have reported no differences in neurocognitive performance following a SRC. Sufrinko et al.[115] examined sex differences in neurocognitive performance in adolescents aged 9–18 years. Their results revealed no differences between male and female concussed athletes on any of the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) neurocognitive assessment outcomes.[115] Similarly, Zuckerman et al.[116] reported no differences on neurocognitive performance among male and female adolescent soccer athletes. Discrepancies in findings may be due to methodological differences such as age, neurocognitive outcome measures and sample size differences.

Dizziness has been reported as the second most common self-reported symptom by concussed athletes.[88,92,117,118] Athletes who report dizziness as a symptom, typically present with obvious balance and vision difficulties.[119] With respect to the prominent symptom of dizziness, it has become apparent that SRC testing should include a vestibular/ocular component in the assessment and management. Very little research has examined sex differences in vestibular and ocular outcomes following a SRC. Currently, the Balance Error Scoring System (BESS) is the most frequently used evaluation for assessing balance following a SRC. However, two new measures, the Vestibular and Ocular Motor Screening (VOMS) and the King-Devick (KD), are up-and-coming in vestibular and ocular testing.

2.1.4.3. Vestibular-Ocular Motor

Some researchers have suggested that sex may affect an athlete's vestibular and ocular outcomes after a SRC. One study administered the VOMS to concussed athletes and found female athletes performed worse on the vestibular and ocular reflex (VOR) component of the VOMS compared to male athletes.[115] However, the other reflex components did not show significant differences based on sex, which lead researchers to believe that only certain vestibular impairments may display sex differences, after sustaining a SRC.[115] Recently, sex differences were found in a study assessing dizziness and vestibular-oculomotor performance at 1, 2, 3, and 4 weeks post-concussion.[50] Overall, reported dizziness and vestibular-oculomotor symptom scores were greater for females and lower for males at each time point.[50] These results are indicative of a longer recovery on vestibular and ocular outcomes in female athletes following a SRC. Lastly, Covassin and colleagues[103] results found college female athletes scored significantly worse on the BESS than male college athletes, however high school male athletes scored slightly worse than high school female athletes on the BESS. Similarly, chin et al. also found high school and collegiate male athletes performed worse on the BESS, compared to high school and collegiate female athletes.[104] In contrast, other researchers have not found sex differences among vestibular/ocular motor performances. In a recent study by Pearce et al.,[57] near point convergence was assessed in males and females following their SRC. Results indicated that sex did not have an impact on convergence insufficiency, which was reported within a portion of the study population.[57] Another study found similar findings of no sex differences, however this study evaluated the KD and the modified BESS.[120] Likewise, Sufrinko et al.[115] reported no significant differences between males and females following a SRC on the BESS.

2.1.4.4. Explanations to Sex Differences

Researchers conducting epidemiological studies have identified differences in SRC incidence between male and female athletes. Possible explanations of why differences are seen with concussed females are attributed to neck muscular strength[121], less neck girth[121], less head-neck segment[121], greater head neck peak angular acceleration[121], reporting rates[117], the physiological system.[101,122,123] Researchers have reported that physically active females had less neck strength (49%), neck girth (30%) and head mass (43%), resulting in lower levels of head-neck segment stiffness (29%) compared to their male counterparts.[121] In addition, Tierney et al.[121] found 50% greater head-neck segment acceleration and 39% displacement than males. Tierney et al.[124] further investigated sex and soccer headgear no head impact kinematics and dynamic stabilization during soccer heading. They also found that female soccer players exhibited greater head accelerations (32-44%) compared to male soccer players.[124] However, Lovely and colleagues[125] did not find significant difference between male and female soccer athletes in neck strength or time to peak torque. Another area of concern for investigators is the physiology of males and females and whether estrogen has an effect in regards to a SRC.[122] Animal models have shown that estrogen treatment before experimentally induced brain injury has protective effects for male rats, but detrimental effects for female rats.[122] Also, sex differences have been attributed to neuroanatomical cerebral blood flow in the brain.[101,123] Researchers have suggested that females have a higher cerebral blood flow rate, coupled with a higher basal rate of glucose metabolism which may exacerbate the neurometabolic cascade.[122] Considering differences in neuroanatomy, females have a greater area of unmyelinated neuronal processes, while males have a greater number of cortical neuronal densities.[101,122] Lastly, it has been reported that females have more knowledge in regards to SRCs and report more than their male counterparts.[96,117] Reasons to why males do not report their SRCs were due to not wanting to leave the game/practice, fear of letting teammates/coaches down, not knowing and understanding the seriousness of a SRC.[117,126,127] Thus, it may be important to manage females differently with a more conservative or targeted rehabilitation and we should consider differences among biomechanics, physiology, and reporting rates.

Overall, a majority of the SRC literature suggest that differences exist in the assessment and management among concussed male and female athletes. Moreover, females are at a greater risk of SRCs, greater neurocognitive impairments, more self-reported symptoms, and longer recovery times. As a result, it is vital that clinicians utilize an individualized, multi-faceted approach in their assessment and management SRC practices and the "one size fits all" criteria should not be used in the management and return to play decisions. Furthermore, healthcare professionals should be aware of potential sex differences between male and female concussed individuals and should compare symptoms, post-concussion neurocognition, vestibular/ocular motor test results to either the athlete's baseline test or to sex comparable norms.

2.2. Assessment and Management of Sport-Related Concussions

2.2.1. Symptoms

Concussed athletes can present with a wide variety of signs and symptoms, which can occur alone or in combination with each other, thus making every concussed individual a unique case. While some athletes experience symptoms immediately, other athletes may experience delayed symptoms that can last hours, days, weeks or months. Self-reported symptoms, both at baseline and post-concussion, help provide subjective information that an athlete is experiencing, along with the severity, duration and intensity of those signs and symptoms. It is recommended to use a standardized symptom checklist, as they provide moderate-good sensitivity to SRCs.[110,128,129] There are numerous tests for symptom monitoring, which include the post-concussion symptom scale,[130] head injury scale,[131] concussion symptom inventory[132] and the Sport Concussion Assessment Tool 5 (SCAT5).[9] Within these scale, there are over 20 symptoms that an athlete may experience after sustaining a SRC. Furthermore, the evaluation of symptoms with a symptom checklist is a quick and cost-efficient practice for sports medicine personnel to implement in their clinical evaluation of concussion.[133] When conducting a baseline assessment of signs and symptoms, healthcare professionals will be provided with an accurate read of what normal symptoms and their intensities are for that particular athlete. Individuals may present with symptoms and some severity on their baseline examination, which further outlines the importance of a symptom assessment prior to the start of an athletic season. It's been reported between 50-92% of athletes, may experience at least one symptom during their baseline assessment.[134-136]

When an athlete sustains a SRC, he/she may present any of the following signs of injury: lying motionless on the playing surface, balance/gait difficulties/motor incoordination/stumbling, slow/labored movements, disorientation or confusion, inability to respond appropriately to questions, blank or vacant look, facial injury after head trauma, loss of consciousness (LOC), and/or inappropriate emotion or behavioral reactions.[9,11] Additionally, it is important to examine retrograde and anterograde amnesia after a sustained SRC. Retrograde amnesia is defined as the inability to recall events in which occurred before the time immediately preceding the SRC, whereas anterograde amnesia refers to the inability to recall events immediately following the SRC.[137] Lastly, it is vital to assess the Glasgow Coma Scale, which involves the level of consciousness for eye, verbal and motor responses.[138]

In addition to these commonly observed signs of a SRC, athletes may self-report a variety of somatic, cognitive, emotional and sleep symptoms.[9] Somatic symptoms are those that physically affect the body and can include headache, nausea/vomiting, sensitivity to light or noise, sleep disturbances, and balance problems. Cognitive symptoms affect the mental abilities and processes, which can include difficulty concentrating or remembering, confusion, fogginess and memory loss are present following a concussion. Emotional symptoms are those causing a change in personal lability such as irritability, sadness, nervous/anxious.[9] The most commonly reported symptom, and is the hallmark symptom of a SRC, is a headache. Previous research has indicated that between 50-95% of individuals suffering a SRC, report with a headache.[86,110,131,139,140] In addition to headaches, researchers have determined the following symptoms to be common among high school and collegiate athletes: dizziness, fatigue, difficulty concentrating, visual disturbances and feel like in a fog.[25,88,92,139,141] Previously, LOC was considered a key identifier of a SRC, however, less than 10% of all concussive injuries report having a LOC.[11,90,92,142-144]

Healthcare professionals are not only responsible for detecting, assessing, managing and making return-to-play decisions regarding SRCs, but they also need to rely on athletes being honest and knowledgeable of the signs and symptoms of a SRC. Currently, consensus statements, media, and general public awareness are improving the detection and education of SRCs to athletes, coaches, parents, referees, administrators, and clinicians.[9,11] However, it is not surprising that many SRCs still go undetected or unreported. Undetected or unreported SRCs can lead to an increased risk of subsequent injury, prolonged recovery and long-term consequences in the student-athlete.[145,146] Athletes may fail to recognize that a SRC has occurred if they are unfamiliar of the 20+ symptoms of a SRC or only experience less commonly recognized symptoms. Other reasons why SRCs may go undetected or underreport include did not feel it was serious enough to warrant medical attention, did not want to be removed from play, did not want to let the teams down lack of knowledge; internal pressure and sport culture. [96,117,126,147]

2.2.2. Neurocognitive Testing

Another main area of SRC evaluation and management is neurocognitive testing. Traditionally, paper and pencil neurocognitive test batteries were introduced in the 1980s, however in the past two decades, computerized neurocognitive tests have been shown to be more sensitive, efficient and convenient than the traditional tests.[17] In addition, it has several claimed advantages over the traditional paper and pen tests including the ability to: 1) baseline test multiple athletes simultaneously, 2) administer and interpret tests in the absence of neuropsychologists, 3) maximally standardize components of test administration, 4) readily use alternate test forms (randomized presentation of stimuli), 5) quantify reaction time, 6) take advantage of centralized data repositories, 7) athletes serve as their own control, which minimizes any confounding factors such as age, sex, learning disability.[148,149] Lastly, neuropsychological testing has been the gold standard in documenting deficits in cognitive function and is useful in detecting deficits following a SRC.[18] Yet when used in isolation, this technique does not provide clinically adequate sensitivity to concussion.[128,143,150] Therefore, neurocognitive testing should never be used in isolation, but rather in conjunction with symptom and motor-control assessments to support the clinical assessment and management. However, there is controversy among computerized neurocognitive testing such as baseline testing practices (i.e. testing athletes in group settings that contribute to poor estimation of premorbid abilities),[151,152] limited assessment and psychometrics training of some professionals who administer and interpret the tests, and the fact that much of the research has been conducted by the test developers themselves.[153]

Neurocognitive test batteries administered to concussed athletes should evaluate multiple aspects of cognitive function. The neurocognitive domains most susceptible to change in the days following a SRC include attention and concentration, information processing speed/efficiency, learning and memory, working memory, executive function and verbal fluency.[10,154] These neurocognitive domains can be found in both pencil and paper and computerized tests. Common paper and pencil tests include the Digit Span, Controlled Oral Word Association Test, and Hopkins Verbal Learning tests which were most commonly targeted at older collegiate and professional athletes that participated in sports with a high risk of a SRC.[10,155] The most common computerized tests include Automated Neuropsychological Assessment Metrics (ANAM), Cogstate Axon, Concussion Vital Signs, Headminder Concussion Resolution Index (CRI), and Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT).[10] Computerized neurocognitive testing has been shown to be effective in identifying the subtle changes in cognitive function following concussion.[156]

During the early phases of neuropsychology in assessing and managing SRCs, brief batteries were comprised of the traditional paper and pencil tasks. Traditional tests are reasonably reliable, valid and sensitive to the effects of sports concussion.[18,157] They can be selected to fit the specific needs of the athlete and domains of neuropsychological importance.[158] However, traditional tests require face-to-face examination, which may introduce variance in test administration and scoring. These tests are also more labor-intensive, especially in sports settings, while conducting baseline testing in large numbers of athletes.[158] While effective in distinguishing between concussed athletes and controls in the hours and days following mTBI,[18,155,159] these batteries were difficult to administer to large groups of individuals because they required one-on-one test administration. Belanger and Vanderploeg[160] conducted a meta-analysis on six cognitive domains between concussed and controls. They found an overall effect size for acute assessment of SRCs (d = 0.49) to be comparable to that of mTBIs in the general population (d = .54).[160] Effect sizes for studies employing a control group were large (d = 0.89), whereas those based on intraindividual comparisons (baseline-post-injury) were less robust (d = 0.19), largely due to practice effects.[160] Acute effects of concussion were greatest for delayed memory, memory acquisition, and global cognitive functioning.[160] No significant effects were found after 7-10 days post-injury although the authors did note that delayed memory remained problematic 7 days post-injury in studies that employed a control group.[160]

More recently, computerized batteries are portable and efficient for the collection, synthesis and storage of large amounts of data. Clinical end-user reports are often immediately available. Broglio and Puetz[56] examined 39 studies spanning 4,145 concussed athletes and controls, on neurocognitive function. They reported an average effect size of -0.81 for neurocognitive functioning assessed acutely, with larger effect sizes for studies employing a control group (g = -0.92) compared to those without a control group (g=-0.63).[56] Reduced effects were found for all neurocognitive testing in follow-up assessments.[56] Using an average retest interval of 6 days, Iverson, Lovell and Collins[161] reported test-rest correlations ranging from .67 to .86 on the four major ImPACT domains. In contrast, Broglio and colleagues[128] reported low to moderate test-retest stability on three contemporary computer-based programs with ICCs of .15 to .65. In terms of establishing sensitivity and specificity, the assessment period following a SRC must occur while the neurocognitive effects of a concussion are most evident. It is well established that approximately 80–90 % of adult athletes will self-report a full symptom recovery within 7 to 10 days,[86] and that effect sizes on cognitive testing are largest during the acute period within the first 7 days after injury.[56,160]

2.2.3. Vestibular and Ocular Motor Testing

Another imperative area of interest for SRC assessment and management practices include neuromotor and motor control testing. It is recommended that all athletes should have a clinical neurological assessment (including evaluation of mental status/ cognition, oculomotor function, gross sensorimotor, coordination, gait, vestibular function and balance) as part of their overall management care.[9,10] Changes in motor control after a sustained SRC have been documented in several areas, including gait,[162,163] postural control,[12,164-166] and hand movement.[167] Furthermore, the assessment of 1 or more motor-control domains can provide valuable information for SRC assessment and management.[10] Overall balance deficits after injury have been attributed to failure to integrate sensory information arising from the vestibular and visual components of the balance mechanism.[164-166] The most popular and widely used by clinicians to assess vestibular and ocular-motor dysfunction relayed to balance is the Balance Error Scoring System (BESS).[10,168] Recently, new tools have emerged that have shown promise in assisting in the evaluation of vestibular and ocular-motor dysfunction related to SRCs that are not currently highlighted in the position and consensus statements.[169-173] Examples of these newly developed SRC tools include the King-Devick (K-D), Sway Balance, and Vestibular and Ocular Motor Screening (VOMS) tests.

Recently, researchers have reported that vestibular impairments are common after a SRC and may delay recovery from this injury.[21,174] Dizziness has been reported by 50% of concussed athletes[175] and is associated with a 6.4-times greater risk, relative to any other on-field symptom, in predicting protracted (21 days) recovery.[176] The vestibular system is a complex network that includes small sensory organs of the inner ear and connections to the brainstem, cerebellum, cerebral cortex, ocular system, and postural muscles.[177] This system provides information regarding head movements and positions to maintain visual and balance control and consist of two distinct functional units, 1) vestibulo-ocular system and 2) vestibulospinal system.[177] The vestibulo-ocular system maintains visual stability during head movements, whereas the vestibulospinal system is responsible for postural control.[177] Impairments in the vestibulo-ocular system commonly manifest as symptoms of dizziness and visual instability, while the vestibulospinal system dysfunction commonly results in disrupted balance.[178] Because these two functional vestibular networks do not share identical neuronal circuitry, it is possible to have impairments of the vestibulo-ocular system without impairments of the vestibulospinal system.[179] In addition to vestibular impairments, ocular motor impairments are also common after concussions.[169] Nearly 30% of concussed athletes report visual problems during the first week after the injury.[175]

It is vital to understand the central nervous system's (CNS) feedback mechanism for maintaining postural equilibrium. Maintaining equilibrium requires the CNS to process and integrate afferent information from the visual, somatosensory, and vestibular systems to execute appropriate and coordinated musculoskeletal responses.[26] Feedback, obtained from sensors housed within the three systems, sends commands to the muscles of the extremities, which then generate an appropriate contraction to maintain postural stability.[180,181] The primary purposes of the human vestibular system are to maintain the eyes fixed on a stationary target in the presence of head and body movement and maintain balance in conjunction with additional information from visual and somatosensory inputs.[26] To accomplish the first, the semicircular canals of the vestibular labyrinth sense angular acceleration of the head, converting it to velocity information, and sending it through the vestibulo-ocular reflex pathways to the ocular muscles.[26] Secondly, balance is maintained by central integration of vestibular, visual, and somatosensory orientation information.[26] The vestibular system provides angular information from the semicircular canals and linear acceleration information from the utricles and saccules of the inner ear and transmits it via the vestibulospinal spinal tract to the spinal and lower extremity muscles.[26]

Balance assessments can be accomplished using a variety of techniques and tools capable of quantifying or qualifying different characteristics of balance. Balance can be assessed utilizing static conditions, dynamic conditions or more functional tasks. Postural stability deficits are commonly seen in 30% of athletes suffering a SRC.[182] Additionally, balance disturbances have been noted to return to normal within 72 hours; however, prolonged damage may last more than 7 days beyond the initial injury.[182,183] Currently, force plate technology is the gold standard for balance measurement.[184] Additionally, newer postural control applications using mobile technology are now emerging for assessing SRCs. However, clinicians often do not have access to research caliber balance technology or paid prescriptions to mobile applications and must rely on efficient, and cost-effective balance tests.

The BESS test is one of the most commonly used balance measures used by researchers and practicing clinicians. Guskiewicz, Ross, and Marshall[166] conducted a study that investigated the postural stability following a SRC in collegiate athletes. Participants underwent pre-season BESS baseline testing and were given a matched control following a concussive event.[166] The concussed subject and their matched control were reassessed on the SOT and BESS at days one, three, and fives following injury.[166] Results found that injured subjects had significant decreases in postural stability at day one compared to their own baselines and the performance of their matched control, while no differences were seen at the other two time points.[166] Return back to BESS baselines for the concussed subjects occurred between days one and three post-injury.[166] Another study conducted by Guskiewicz[26], examined the sensitivity of the BESS test in college football players. The study revealed that concussed football players deviated from their baseline BESS measurements by 5.7 errors when tested immediately following the game or practice in which the injury occurred.[26] Systematic reviews have also been conducted on the BESS test.[182,185] Both studies found moderate to good reliability and moderate to assess balance disturbances in athletes with concussions.[182,185] As a result, it is important for healthcare providers to choose a balance measure that is feasible in their setting and that those administering the assessment are properly trained in the evaluation and return to play management of SRCs.

Until recently, all vestibular impairments after SRCs were commonly assessed using the BESS[186] or the SOT.[187] However, these measures are static assessments and only represent the vestibulospinal aspect of the vestibular system and do not address dynamic aspects of the vestibular system or vestibulo-ocular control.[169] Vestibular and oculomotor impairment and symptoms may be associated with worse outcomes in the subacute (1 week–3 months) time periods after a SRC.[171,176] Furthermore, Corwin et al.[171] observed that patients with vestibular insufficiency at their first clinical visit were more likely to exhibit protracted recovery, specifically, abnormalities on VOR testing or tandem-gait performance, resulted in an average recovery time of 59 days.[171] Mucha et al.[169] described and provided initial data for the internal consistency of a new brief clinical screening tool of vestibular and ocular motor impairments and symptoms after SRCs and has been previously reported to have moderate-high reliability, validity, and sensitivity when tested over multiple trials in concussed athletes.[169,173,188] Their results found 61% of patients reported symptom provocation after at least one VOMS item.[169] Furthermore, Elbin et al.[189] examined concussed athletes on all components of the VOMS and found significance at two timepoints (1-7 days and 8-14 days) compared to baseline. Additionally, change scoring revealed postinjury impairments compared with baseline on all components at 1 to 7 days, however impairments at 8 to 14 days were revealed only for the vertical vestibular oculomotor reflex and vestibular motor sensitivity.[189] The vestibular-ocular reflex (VOR) and the visual motion sensitivity (VMS) components of the VOMS were most predictive of being in the concussed group.[169] A near point of convergence (NPC) distance 5 cm and any VOMS item symptom score ≥2 resulted in an increase in the probability of correctly identifying concussed patients of 38% and 50%, respectively.[169] Moreover, convergence insufficiency (CI) is a common binocular vision deficit after a SRC.[57] CI may result in visual discomfort and vision-mediated functional difficulties such as slowed reading and compromised attention, leading to impaired academic, work, and sport performance.[57] Two authors[57,190] examined CI in concussed athletes approximately 5 days after their sustained SRC and found that the CI group had significantly poorer performance on the near point convergence (NPC) compared to the normal group and the CI group took significantly longer to recover from their SRC than athletes with normal NPC. Lastly, it important to identify specific vestibular/ocular motor abnormalities and their associated prognosis, so it will aid clinicians in the management of concussed athletes.

2.2.4. Evaluation and Return to Sport Participation

It wasn't until 2009, that the US legislation addressed reporting, documentation and management of concussions.[191] The first concussion law was signed on May 14th, 2009, by the governor of the state of Washington, after a devastating head injury to a 13-year-old, high school football player.[192] Zackery Lystedt suffered an initial concussion in the second quarter of the football game and was allowed to return back to play, despite suffering from multiple signs and symptoms.[191] He later sustained multiple blows during the game, collapsed on the field and underwent emergency brain surgery.[191] Fortunately, he survived, but had significant neurologic injury and permanent disability.[191] This incident lead to the creation of the Zackery Lystedt Law, which went into effect in 2009, and has three essential components: 1) education of athletes and parents/guardians regarding concussions, 2) removal of the athlete from practice or play at the time of a suspected concussion or head injury, and 3) return to practice or play only with the written permission of a licensed health care provider trained in the evaluation and management of a concussion.[192] Since the creation of the Zackery Lystedt Law in 2009, all 50 states and the District of Columbia have enacted a concussion law that are centered around the three main pillars of the Zackery Lystedt Law. While these laws show promise to the people of the states, additional research is needed to learn if these strategies are being implemented and are educating the community, while protecting our youth from SRCs. Additionally, there are several similarities found between most states which include coverage entities, information forms, and education programs, however there are major differences between states that are based on the compliance of all three pillars of the Zackary Lystedt Law, immediate removal, written clearance, and who clears the concussed athlete for return-to-play.

To-date, there are no gold standards pertaining to the assessment and management of SRCs. However, it is important to establish a concussion management protocol to maintain consistency of care and ensure that proper procedures are followed when making critical decisions.[193] Several concussion position[10] and consensus statements[9,11] and state legislation have discussed the appropriate actions when evaluating a concussed athlete. These actions can include 1) the player should be evaluated by a physician or another licensed healthcare professional, if they show any signs and/or symptoms of a SRC, 2) the concussed athlete should be safely removed from practice/play and be referred to a physician as soon as possible and should not be allowed to return to play on the day of injury, and 3) the athlete should not be left alone after the injury and the healthcare provider should monitor for deterioration over the initial few hours after injury.[9,11] Once a healthcare professional conducts a medical assessment, which should include a comprehensive history and detailed neurological examination including a thorough assessment of mental status, cognitive functioning, sleep/wake disturbance, ocular and vestibular function, gait and balance, the provider should determine the clinical status of the patient and the need for emergent neuroimaging to exclude a more severe brain injury.[9,11]

The process of recovery and return to sport participation, after enduring a SRC, follows a graduated stepwise progression. After a period of initial rest (24–48 hours), symptom-limited activity can begin, while staying below a cognitive and physical exacerbation threshold (Table 1).[9,11] Once concussion-related symptoms have resolved, the athlete should continue to proceed to the next level if he/she meets all of the criteria, without a recurrence of concussion-related symptoms.[9,11] Each level of the progression should take 24 hours, which will result in a minimum time of one week to proceed through the full rehabilitation protocol, once the concussed athlete is asymptomatic.[9,11] If any concussion-related symptoms occur during the stepwise approach, the athlete should return back to the previous asymptomatic level and attempt to progress again, after being free of concussion-related symptoms for a further 24-hour period at the lower level.[9,11] In athletes who experience prolonged symptoms and resultant inactivity, each step may take longer than 24 hours, due to the limitations in physical conditioning and recovery strategies.[9] In addition, the time frame for return to sport participation may vary due to a variety of risk factors, thus the management of the concussed athlete should be individualized.[9] In conjunction with the graduated stepwise progression protocol, each concussed athlete should return to their pre-injury baseline normative values on symptoms, neurocognitive and postural stability tests.[9] Lastly, a concussed athlete should not return to athletic participation until evaluated and cleared by a physician or a licensed healthcare professional, specifically trained and experienced in concussion evaluation and management.[9]

Table 1. *Graduated Return to Sport Strategy.* From "Consensus statement on concussion in sport – The 5th international conference on concussion in sport held in Berlin, October 2016," by McCrory, P., et al. 2017. *British Journal of Sports Medicine.* 47(5), 250-258.[9]

Stage	Aim	Activity	Goal
1	Symptom-limited activity	Daily activities that do not provoke symptoms	Gradual reintroduction of work/school activities
2	Light aerobic exercise	Walking or stationary cycling at slow-medium pace No resistance training	Increased heart rate
3	Sport-specific exercise	Running or skating drills No head impact activities	Add movement
4	Non-contact training drills	Harder training drills May start progressive resistance training	Exercise, coordination and increased thinking
5	Full contact practice	Following medical clearance, participate in normal training activities	Restore confidence and assess functional skills by coaching staff
6	Return to sport	Normal game play	

Most position and consensus statements regarding concussions provide recommendations for both physical and cognitive rest, however these guidelines do not provide information on the timing, duration, type or other specifics related to physical and cognitive rest.[194] This has lead researchers and clinicians to question whether rest is the best strategy after enduring a SRC and some evidence[195,196] suggest that active treatment strategies may be more beneficial to patients during the recovery process. According to a recent systematic review[194], their findings suggest that the initial period of moderate physical and cognitive rest may improve outcomes during the acute post-injury phase and additional research is needed to empirically validate the effectiveness of graded return to sport progressions. By adding high-quality, prospective research to the body of literature in regard to rest and return to sport progressions, this will provide an evidence-based guide for managing patients with a SRC.

2.2.5. Return to Learn

Following a SRC, the top priority for adolescents is a safe and effective return to school, followed by a successful return to sport. Moreover, adolescents should not return to sport until they have successfully returned to school, however early introduction of symptom-limited physical activity is appropriate.[9] While return to play practices have been extensively researched and protocols are widely adapted, returning to school or return to learn, have received considerably less attention. A few authors[197,198] and consensus statements[9,11] have developed recommendations for academic re-entry and accommodations after sustaining a SRC, with practical guidance for clinicians. School institutions are encouraged to have a SRC policy that includes education on SRC prevention and management for all parties involved and should offer appropriate academic accommodations, support, and a graduated return to school strategy (Table 2).[9] Although all 50 states have implemented legislation policy regarding return to sport,[199] there is no consensus on return to learn guidelines at the state or national level. In fact, return to learn laws are present in only eight states, with most of the laws (75%) holding schools responsible for return to learn management.[200] Furthermore, consensus statements suggest that teachers and other school staff are responsible for implementing recommendations, and for ensuring that the recovering student's needs are considered and addressed.[9,11] However, a recent study shown an absence of an evidence-based return to learn protocol (26.1%) from their total respondents and only 38.1% of the respondents actually utilized the protocol that was in place.

Table 2. *Graduated Return to School Strategy.* From "Consensus statement on concussion in sport – The 5th international conference on concussion in sport held in Berlin, October 2016," by McCrory, P., et al. 2017. *British Journal of Sports Medicine.* 47(5), 250-258.[9]

Stage	Aim	Activity	Goal
1	Daily activities at home that do not give the child symptoms	Typical activities (i.e. reading, screen time, etc.) that do not increase symptoms Start with 5-15 mins at a time and gradually build up	Graduated return to typical activities
2	School activities	Homework, reading or other cognitive activities outside of the classroom	Increase tolerance to cognitive work
3	Return to school part time	Gradual introduction of schoolwork Partial school day or with increased breaks during the day	Increase academic activities
4	Return to school full time	Gradual progress of school activities until a full day can be tolerated	Return to full academic activities and complete missing work

Recommendations for return to learn have focused on cognitive rest, which typically entails complete mental rest from activities requiring attention (e.g., electronic technology, reading, homework), to limiting such activities or performing them with accommodations (e.g., taking breaks, reducing time spent engaging in cognitive activities, using additional time for assignments, part-time or gradual return to school) and then, resumption of full cognitive schoolwork.[201] The rationale for prescribing cognitive rest is to keep cognitive exertion below the level that triggers exacerbation of symptoms and allows the brain to heal. However, evidence supporting complete activity restriction/rest versus limited cognitive rest is mixed, with some research showing negative consequences of prescribing cognitive rest altogether (e.g., detrimental impact on quality of life when removed from validating life activities in combination with physical deconditioning).[202-204] Despite the absence of empirical literature, a majority of surveyed athletic trainers (AT) incorporated some form of cognitive rest in their SRC management protocol based on anecdotal resources.[205]

School personnel, (i.e. school nurses, school counselors, and neuropsychologists) and healthcare providers play a vital and supportive role in the delivery of school care for the returning concussed student. Healthcare providers can set specific cognitive targets that should be individually-based, while working with school personnel to provide their expertise in developing academic accommodations and adjustments, which will result in an established interdisciplinary approach for managing student-athletes with a SRC. Both parties can work together with the student and parents/guardians to educate and provide guidance regarding activity restrictions and allowances when the student is not in school or returning to sport.[206] It is important to note, that some students might find relief from a small number of accommodations for a few days, while others with persistent symptoms might benefit from more accommodations and a careful management plan to facilitate their academic success. Future research is warranted to examine the validity of the return to learn progressions and specific recommendations for managing activity level and symptom response during this progression.

2.3. Driving

2.3.1. Car Collision Rates and At-Risk Populations

Driving is considered an activity of daily living, however is carries the risk of injury and death. Furthermore, motor-vehicle accidents are a public-health epidemic in the US and across the world, and is the leading cause of injury and death.[207] According to the Centers for Disease Control and Prevention[208], these deaths led to approximately 1.2 million years of potential life lost in the US and over 2 million people were injured in 2015, which resulted in more than $380 million in direct medical costs alone.[209] More specifically, for every one person killed in a motor vehicle accident, eight people are hospitalized and 99 people are treated and released from emergency departments.[208] Additionally, one in three crash deaths in the US involved drunk driving, and almost one in three involved speeding.[209] Lastly, the US crash death rate was more than twice the average of other high-income countries that were comparable to the US.

In the US, motor-vehicle collisions are also the leading cause of death among 16 to 19-year-olds in the US, with almost 2,500 teens killed and 300,000 injuries annually.[210] In addition, teen drivers are nearly three times more likely than drivers aged 20 and older to be in a fatal car accident.[211] When examining risk factors associated with teen deaths, males were two times more likely to have a motor vehicle death than their female counterparts, teens driving with teen passengers, and newly licensed teens (16-17) had nearly twice as many fatal crash rates as compared with 18-19 year olds.[210] Other factors that put teens at risk include, underestimating dangerous or hazardous and distracting situations, risk taking (i.e. speeding), lower rates of seat belt use, sleeplessness, and alcohol use.[210]

2.3.2. Sport-Related Concussion Risk

Motor-vehicle collisions typically happen, due to a number of factors such as a loss of cognition and focus, however these areas are often seen in concussed patients. Presently, there is limited research on the safety of continuing to drive after sustaining a SRC and thus, recommendations have largely been based upon clinical experience and expert opinion. Furthermore, since the management practices are largely focused on the return to sport and return to learn progressions, there are other significant activities of daily life that may be affected after enduring a SRC, such as driving. Driving can be a potentially dangerous activity, especially for new and young, inexperienced drivers. Moreover, driving a motorized vehicle involves individuals to have adequate emotional control, cognition, attention, and motor coordination, however, individuals with a SRC often have impairments in these areas.[28] Since return to drive is not a critical component of SRC guidelines, we may be putting athletes and other individuals on the road at risk of serious injuries.

There are only a few studies that examine simulated driving performance in mTBI patients[28,212-214] and even fewer studies examining simulated driving performance in concussed college students and student-athletes.[41,42] Three studies[28,212,213] observed patients from a hospital, within the first 72 hours of sustaining a mTBI, completed the University of Queensland Hazard Perception Test (UQ-HPT). Both studies[28,213] found the concussed group to have significantly slower response times on the hazard perception test and the Glasgow Coma Scale scores were not significant related to their hazard perception response. Additionally, Preece et al.[28] found significant correlations within the concussed group between post-traumatic amnesia and their hazard response. In addition, participants with a mTBI were significantly faster in anticipating traffic conflicts than participants with a moderate to severe TBI.[28] The same author published another article related to self-reported concussions on cumulative or enduring effects of driver's anticipation of traffic hazards. They found no significant effect on past medical history of any number of concussions on the hazard perception test response times.[214] Similarly, pairwise comparisons showed no significant differences between the hazard perception test response times of individuals reporting a concussion within the previous 3 months, individuals reporting an earlier concussion, and the controlled group.[214] In contrast, a quasi-experimental case-control design study examined mTBI and minor orthopedic patients on various tests, such as the Mini Mental State Examination (MMSE), Occupational Therapy-Drive Home Maze (OT-DHMT), Road Law Road Craft (RLRC), and the UQ-HPT.[212] Their results found at 24 hours post assessment, that the concussed group has significantly slower times on the OT-DHMT than compared to the minor orthopedic group, but not on the MMSE, RLRC and the UQ-HPT.[212] At a two-week follow-up, only 26 of the 60 mTBI participants had returned to driving. Delayed return to driving was reported due to: "not feeling 100% right", headaches and pain, and dizziness.[212]

When exploring the literature on simulated driving performance in concussed college students and student-athletes, one study found concussed participants during their asymptomatic stage, committed 32% more lane excursions and exhibited greater standard deviation of speed and lateral position, but did not differ in centerline crossing, total crashes, or tickets compared to their match controls.[41] Additionally, the same study also inspected correlations between neuropsychological assessments and simulated driving performance. Their results found several strong correlations on symbol digit modalities, Rey Osterrieth Complex Figure accuracy, and the CNS Vital Signs verbal memory and motor speed domains with higher rates of lane excursions to the right among the concussed group compared to the control group.[41] Additionally, slower Rey Osterrieth Complex Figure recall time was significantly correlated with more total crashes among the concussed group, as well as worse performance on the CNS Vital Signs cognitive flexibility and executive function received more total tickets, but was not seen within the control group.[41] Lastly, another study[42] examined simulated driving performance immediately after a concussion and after medical clearance was given for return to play. Their results found that concussed college students displayed less deviation (improvement) in speed management in complex curved driving routes from sustaining a concussion to their return to play date, while no differences were seen in center lane management.[42] In addition, they only saw significant improvements on the ImPACT visual memory and processing speed domains from their sustained concussion stage to their return to play stage.[42]

There have been a few studies related to surveying multiple stakeholders (e.g. physicians, nurse practitioners, patients) in regard to the management of driving abilities.[43,49,215-217] Two studies[215,217] surveyed physicians on their decision-making strategies in regards to return to drive after a SRC. The first study introduced a return to drive project as an intervention and found a significant increase in driving recommendations from 9.3% at baseline to 97% in approximately a year and a half.[215] Additionally, on average, physicians estimated that they spent less than 30 seconds per patient on counseling and documentation, which suggest that the intervention did not adversely impact the clinic flow.[215] The other physician study determined which SRC data that was collected on an initial patient clinic visit, might influence physicians to clear an adolescent to return to drive following their injury.[217] In their multivariable analysis, odds of being fully cleared to drive were almost six times greater among patients who were administered computerized neurocognitive test, and stated symptoms of a “headache” and “sensitivity to light”.[217] In addition, each additional 10-millisecond decrease in simple reaction time was associated with a 9% greater odds of being cleared to drive.[217] Lastly, a study by Klein et al.[216] investigated nurse practitioners driving guidance and its clinical basis for restriction or limitation following an adolescent concussion. Approximately, 93.8% provided driving recommendations, with 32.6% based on time, 49.8% based on symptoms, and 28.5% based on healthcare utilization.[216]

Little is known in regard to concussed patient’s intentions of returning to drive, even though concussions could pose a risk to road safety. Eighty-one patients with an mTBI were recruited from an emergency department and completed a questionnaire measuring expectations regarding recovery from their injury and returning to drive.[43] Only 48% of the concussed sample intended to reduce their driving following their injury, compared to the control group, with an average of 17 days either not driving or driving in a reduced capacity.[43] Moreover, those who had not experienced a previous head injury were more likely to intend to reduce driving than those who had a previous head injury (61% vs. 38%, respectively).[43] With the limited research on survey-based studies, literature is needed to expand on the time frame of driving after sustaining a SRC. Similarly, Schmidt and colleagues[49] also found that college student-athletes refrained from driving follow a concussion 43.8% of the time. Additionally, student-athletes who refrained most commonly did so for only 24– 48 h (20.5%), felt ‘‘very unsafe’’ driving a car immediately following injury (38.4%), and refrained from driving because a healthcare provider advised them to (33.3%).[49] When asked whether driving restrictions would influence their decision to report the injury to a health care provider, only 26.6% ‘‘probably would’’ (57/214), 24.8% ‘‘probably would not’’, and 22.9% ‘‘definitely would not’’. Despite generally believing that driving immediately following a concussion is unsafe, a majority of student-athletes did not refrain from driving at any point following their previous concussions. Finally, clinicians should educate athletes and other relevant parties involved on their driving ability, after enduring a SRC and should use driving-related questionnaires as an assessment tool in their practices.

2.3.3. Car Simulators

Driving is an important activity of daily living to most people and an integral part of mobility and independence that affects physical, social, and economic well-being.[218] However, the loss of driving privileges can lead to increased healthcare costs, depression and decreased access to medical care.[219,220] The ability to drive can be affected by various motor, visual, cognitive, perceptual and sensory deficits commonly experienced after neurologic disorders, such as stroke, Parkinson’s disease, Alzheimer’s disease, multiple sclerosis, and traumatic brain injuries. A method of investigating safe, driving performance among patients with neurological disorders is through the use of driving simulators.

Driving simulators can be used to evaluate cognitive impairment and can potentially offer an improved method of evaluating cognitive functions, in the context of an everyday task that has not been available through traditional neuropsychological assessment.[221,222] Unlike static paper and pencil cognitive and vision tests, a driving simulator can evaluate the dynamic aspects of driving skills and abilities that may be impaired by TBI, such as spatial orientation, situational awareness, as well as tactical and operational vehicle control.[221] As mentioned, driving is a complex, cognitively demanding activity, which requires the ability to remain awake and alert, vigilance, making fast and accurate responses, depth and motion perception, spatial orientation and path finding, DA, multitasking, planning and decision making, hazard recognition and avoidance, safety judgments, and emotional self-control.[223,224] Driving simulators provide a safe and controlled setting in which errors can be made without cost to life, health, or property.[225] Moreover, simulators can be programmed to simultaneously collect data related to a large number of these basic and higher-order processes, to determine whether they fall outside the normative ranges. A recent study found that performance in the driving simulator was a better predictor of actual driving skills within the community than was performance in an on-road test.[222] This was because the simulator exposed the driver to a wider range of demands than is safely feasible on the road, while simultaneously measuring both lower-level and higher-level skills in these situations.[222]

Interactive driving simulation models and vehicles are equipped with functional models of systems from the perspective of the operator, providing the functions necessary for a validity of an experiment or a satisfactory training.[226] Modern simulators usually consist of parts of real vehicles or machines and a complex system of a computer-generated virtual reality, which should cover the widest possible range of operator's sensor input, so that it can induce a sense of realistic environment.[226] The first driving simulator was designed by Volkswagen in the early 70's, as 3DOF motion based and was equipped with one screen, which formed the windshield.[226] Driving simulators and the driving simulation technology are said to be a "royal discipline" within the scope of the simulation devices, due to their high technical and spatial demands, and are usually developed and designed in cooperation with university research institutions, state research institutions and car manufacturers.[226]

The STISIM Drive® software is a reliable and validated driving simulation system specifically designed for medical and occupational therapy applications.[227,228] The STISIM Drive® software had been utilized in the literature for testing participants with mild traumatic brain injury (mTBIs), however the STISIM Drive® software has not been used with SRCs previously. This software has been engineered to facilitate the diagnosis, evaluation, treatment, and rehabilitation process of the needs of patients experiencing brain injury or impairment. Additionally, it allows the medical provider to create a database that tracks the treatment routine, driving results (scenario results), and rehabilitation progress for each patient. Within the large portfolio of predesigned scenarios, this study utilized three primary tests: 1) memory, planning, and navigation, 2) car following with DA, 3) passing, gap judging & merging).

2.4. Summary

Driving a motorized vehicle involves individuals to have adequate emotional control, cognition, attention, and motor coordination,[28] however, individuals with a SRC often have impairments in these areas.[9] By having severe signs and symptoms from a SRC, it could influence the way drivers think and act, as well as impair their acceptable decisions, in which it would make it harder to detect and avoid hazards on the road. Thus, in terms of driving risk of crashes, concussed adolescents and college aged student-athletes are at the greatest risk. This study will provide clinicians with various time points (i.e., 72 hours, when asymptomatic and return to participation fully) during the clinical indicators of a SRC recovery, where concussed athletes are safe to return to driving. Even though this would be considered a short duration of testing with concussed individuals, this is the most likely time at which a concussed individual would return to driving. Additionally, this study is vital for ATs in determining recommendations for return to drive and what assessments comprise the best evaluation of return to drive in athletic populations. The preliminary results of this study may help guide future research efforts aimed at developing a comprehensive driving evaluation for individuals with a SRC.

CHAPTER 3

METHODOLOGY

3.1. Experimental Design

A cohort design was used to compare test-retest reliability, simulated driving performance and concussion measures between high school and collegiate athletes with and without a SRC. The independent variables were group (concussed athletes, non-concussed match control athletes), and clinical indicators of SRC recovery (within 72 hours, asymptomatic, return to full participation). The dependent variables were simulated driving performance (i.e. road lane excursions, centerline crossing, car collisions, pedestrian collisions, speeding tickets, stop sign tickets, turn signal usage and DA) and SRC tools which include neurocognition (i.e. verbal memory, visual memory, visual motor speed, impulse control, and reaction time), balance (i.e. total number of firm errors, total number of foam errors), vestibular/ocular motor (i.e. smooth pursuits, horizontal and vertical saccades, convergence, horizontal and vertical vestibular ocular reflex VOR, and visual motion sensitivity), and symptoms (i.e. total number of symptoms, total severity of symptoms). This study was approved by the Michigan State University Institutional Review Board (IRB). Data was collected from August 2018 - March 2019.

3.2. Sample Population and Participant Selection

3.2.1. Participants and Recruitment

Test-Retest Reliability of the STISIM Drive® Software

Students were recruited from Michigan State University's Department of Kinesiology, due to the close proximity of the driving simulator within the building. Professors from three courses within the Department of Kinesiology gave permission and approval to allow their students to voluntarily participate in the described study. The students were rewarded 10 extra credits points within their respective course (Figure 1).

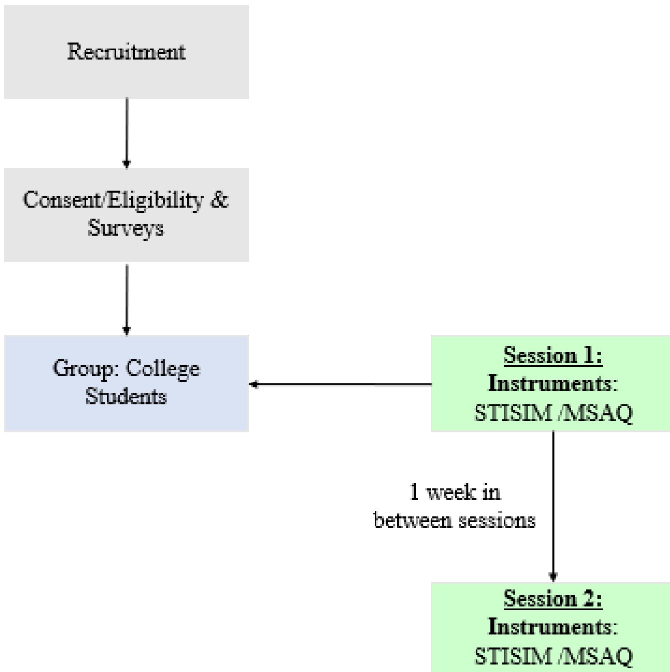

Figure 1. *Procedures of the study.*

Simulated Driving Performance in Concussed and Non-Concussed Athletes

Athletes from a total of 5 high schools and 3 colleges within the state of Michigan were recruited to participate. Of the 5 high schools and 3 colleges, 2 high schools and 2 colleges accepted to participate in the current study. High schools and colleges were selected based on previous history for collecting data in the past 12 years and were in close proximity to the Michigan State University Campus. High school and college AT's were contacted through email and then followed up by a telephone call to participate in the study. Each SRC was verified by an AT and/or MD/DO. All sites conformed to the international recommendations that a SRC recovery is determined by each athlete returning to his/her baseline (all athletes are administered baseline tests as part of their SRC protocol) and to use other multi-faceted measures (i.e. symptoms, cognition, vestibular/ocular motor symptoms, and balance), prior to completing a step-wise exertional protocol.[9] Each participating high school and college had a full-time, licensed AT. Administrators at each school gave permission and approval to allow their athletes to voluntarily participate in the described study. The supervising AT that diagnosed the SRC, asked the injured and match control athletes if they could be approached by the researcher for recruitment into the study. Once the athlete accepted to participate in the study, the researcher contacted the athlete to explain the study to them. If the athletes agreed to volunteer and consent/assent were obtained, participants were screened for participation based on the defined inclusion and exclusion criteria and were allocated to the SRC-injury group or match control group (Figure 2). Athletes were compensated $50 for each visit, for a total of $150 for all visits, as well as the respective AT/physician received $50 for the referral of the athletes.

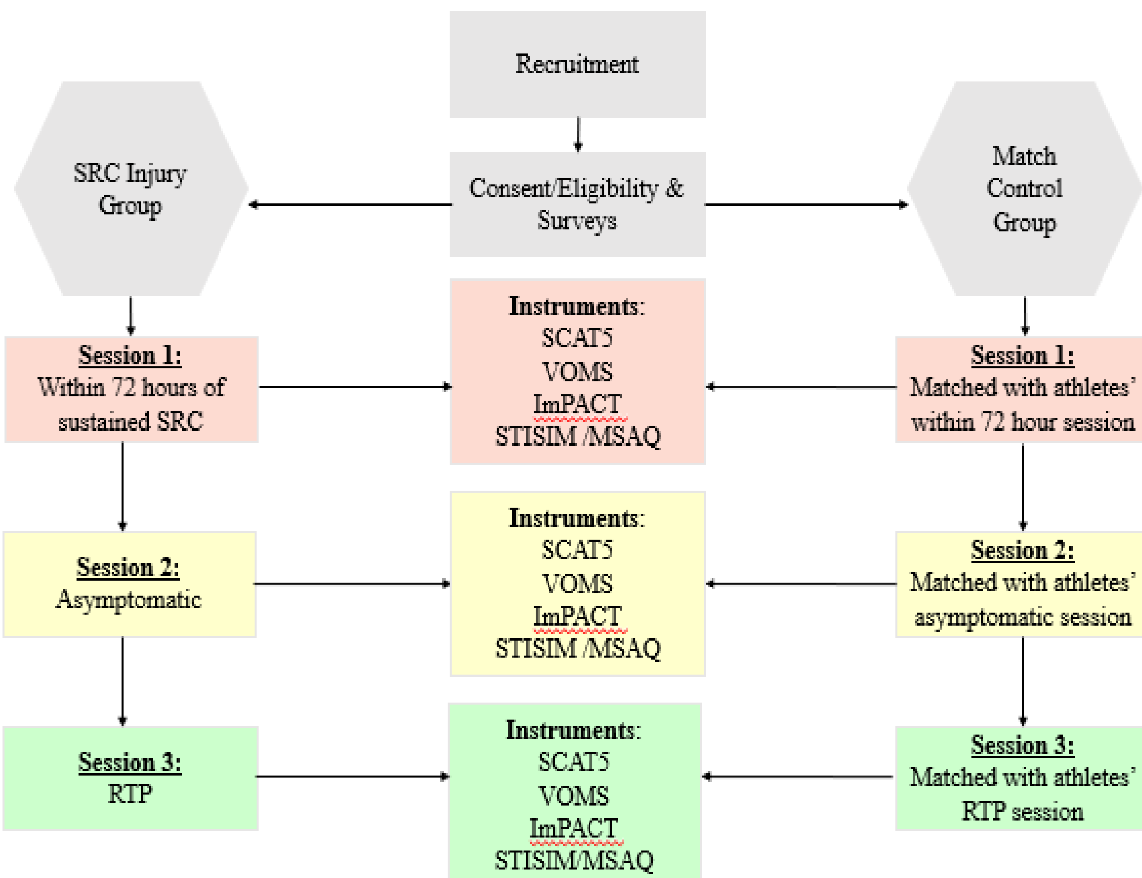

Figure 2. *Procedures of the study.*

3.2.2. Inclusion Criteria

Participants were included in the first purpose if they were 1) between the age of 16-25 years, 2) currently enrolled as a college student, and 3) had a valid driver's license. To be included in the second and third purposes of this study, athletes with a SRC had to meet the following criteria: 1) between the age of 16-25 years, 2) currently participating on a high school, college varsity or club sport, 3) valid driver's license, 4) no major neurological disorder or a history of a SRC within the past 6 months prior to enrollment, 5) enrolled by a research assistant within 72 hours of a sustained SRC, 6) loss of consciousness was less than 20 minutes, 7) no hospitalization, or neuroimaging evidence of structural injury, and 8) SRC was diagnosed by a healthcare professional. Additionally, match control athletes had to meet the following inclusion criteria: 1) between the age of 16-25 years, 2) currently participating on a high school, varsity or club sport, 3) valid driver's license, and 4) no major neurological disorder or a history of a SRC within the past 6 months prior to enrollment. In addition, matched controls were matched based on age, sex and sport of the SRC-injury group.

3.2.3. Exclusion Criteria

Any student or athlete that met any of the following exclusion criteria were excluded from the study: 1) evidence of illicit drug usage, 2) current central nervous system active prescription medications (i.e., analgesics), 3) current or previous history of neurological disorder (i.e., epilepsy) or history of concussion within the past 6 months 4) did not speak or read English, or 5) prior brain surgery.

3.3. Instrumentation

3.3.1. Demographic Survey

The demographic survey consisted of 18 questions for the SRC injury group, 14 questions for the match control and 12 questions for the test-retest group. For all groups, the survey included questions regarding to the participant demographics such as age, sex, date of birth, race, height, weight, handedness, if they wear contacts or glasses, academic year, current GPA ad concussion history. Within the SRC and match control questionnaires, sport demographic questions were asked regarding sport and position. The additional questions for the SRC-injury group included date and time of the injury, where the SRC was sustained (i.e. NCAA practice or competition, high school practice or competition), offensive or defensive play and mechanism of injury (Appendix A-C).

3.3.2. Driving Questionnaire

The driving experience questionnaire consists of 22 questions concerning the participants' driving history. Several questions pertained to the driving license type (i.e., Class C), years of experience driving, hours per week spent driving, and average speed while driving. Additional questions pertained to distractions, total number of driving related tickets, driving under the influence, and seatbelt usage. The questionnaire took approximately 5 minutes to complete (Appendix D).

3.3.3. Sport Concussion Assessment Tool 5 (SCAT5)

The SCAT5 was developed from the original SCAT to help assist healthcare providers in their return-to-play decisions. Additionally, the SCAT5 is the most recent revision of the SCAT in the acute evaluation of a SRC. This SRC evaluation tool can be used on the sideline and during post-concussion evaluation. The SCAT5 includes two primary sections, which are the immediate/on-field assessment and the office/off-field assessment.[11,229] This tool takes approximately 10-15 minutes to complete (Appendix E).

SCAT5: Immediate/On-Field Assessment. The first component includes red flags, observable signs, Maddocks questions, Glasgow Coma Scale and a cervical spine assessment. This study did not assess the red flags, observable signs and Maddocks questions, since the ATs were responsible for assessing and managing the SRCs.

Glasgow Coma Scale. This scale was used to assess the level of consciousness for eye, verbal, and motor responses. If participants were able to open their eyes spontaneously to stimuli, then they would receive a score of 4/4. If athletes were oriented to verbal commands, then they would receive a score of 5/5. Finally, if athletes were able to obey motor commands, then they would receive a score of 6/6. The three components were added together to yield a maximum score of 15.

Cervical Spine Assessment. This assessment was determined by first asking the athlete if their neck is pain-free at rest. If the athlete did not report neck pain at rest, he/she were asked to actively move their neck through a full range of motion. Upon completion of full neck range of motion, the athlete reported if he/she had full range of active, pain-free motion. Finally, limb strength and sensation were tested by asking the athlete to squeeze the examiner's hands and move their toes for limb strength and if he/she had numbness or tingling traveling down their extremities for limb sensation. For each question, the examiner would record a yes or no response from the participant.

SCAT5: Office/Off-Field Assessment. The second component includes the athlete background, symptom evaluation, cognitive screening, and neurological screen. All sections were recorded by the examiner.

Athlete Background. The athlete background section obtains information regarding the athletes' sport, concussion history, years of education, age, sex, dominant hand, diagnosis of headache disorder or migraines, learning disability/dyslexia, ADD/ADHD, depression, anxiety, or any other psychiatric disorder and current medications.

Symptom Evaluation. Participants completed a self-reported symptom scale on how he/she feels on the day they completed their session. There were 22 items, rated on a 7-point Likert scale (i.e., 0 = none to 6 = severe) for the athlete to report. Likert scale scores for the 22 concussion symptoms were added together to get a total symptom severity score out of 132. After completing the symptom inventory, athletes were asked to report if their symptoms were worse with physical or mental activity and their "percent normal" after being prompted with "If 100% is feeling perfectly normal, what percent of normal do you feel?" If athletes did not report 100%, they were asked to briefly explain why.

Cognitive Screening Test. The cognitive screening test is a modified standardized assessment of concussion (SAC) test. The SAC measures orientation, immediate memory, concentration, and delayed recall. The modification to the SAC currently includes the newly revised immediate memory test. The immediate memory test currently has a list of 5 and 10 words, in which this study chose the 10-word list for the immediate and delayed recall sections for the present study. Athletes were presented the 10-word list and were asked to recite them in any order to the researcher. Athletes were presented the same word list for three trials, with a maximum score of 10 for each trial, for a maximum total score of 30. The added option of using a 10 word list per trial could diminish ceiling effects, while preserving continuity with the 5 word list in those settings where ceiling effects are less apparent.[229] In addition, the SAC included the concentration digit backwards test, which is a string of numbers that athletes were asked to repeat backwards. The digit backwards test starts at 3 numbers (i.e., 4-9-3) and progresses up to 6 numbers (i.e., 8-4-1-3-5-7). If the athlete correctly completed the string, he/she progressed to the next string length. If the athlete was incorrect, he/she received a second trial with the same string length. The test was completed if the athlete received two trials wrong within the same string length or the athlete successfully completed all strings. Additionally, participants had to repeat the months of the year backwards and were given a 0 for an incorrect score and a 1 for a correct score. Finally, delayed recall asked the participant to repeat the original list of 10 words from the immediate memory test. Delayed recall was completed after at least 5 minutes had elapsed from the original immediate memory test. The original SAC had a test-retest reliability of 0.64. The validity of the original SAC for each subtest is as follows: Orientation ($r = .36$), immediate memory ($r = .61$), concentration ($r = .68$), and delayed recall ($r = .52$).[230]

Neurological Screen. In the neurological screen, participants were asked to read out loud (i.e., symptoms) in order to determine if they could follow directions without difficulty. Athletes then had the researcher test their passive cervical range of motion and recorded if it was pain-free. Next, athletes were asked to move their eyes from side-side and up and down without moving their head, without having double vision. Lastly, athletes were asked to perform the finger nose coordination test and the tandem gait test. For all the neurological questions, answers were recorded as a yes or no response.

Balance Examination. In addition to the neurological screen, there was a balance examination within this section. Athletes were asked to perform the Modified Balance Error Scoring System Test (mBESS) within the SCAT5. However, this study conducted the full Balance Error Scoring System Test (BESS) for this study. The BESS consists of three stances on a firm and foam surface. The 3 stances consist of a double-leg stance, single-leg stance (non-dominant leg), and tandem stance (one foot in front of the other, heel to toe, non-dominant in the rear). All participants were instructed to stand quietly with their eyes closed and their hands on their iliac crests, in each stance for 20 seconds. Each separate stance was scored individually, and each error performed by the athlete results in a point added to their score. The researcher counted possible errors which included lifting hands off the iliac crests, opening of the eyes, stepping, stumbling, or falling, moving the hip into more than 30 degrees of abduction, lifting the forefoot or heel, and remaining out of the testing position for more than five seconds. If an athlete commits multiple errors simultaneously, only one error was recorded, and the athlete quickly returned to the testing position. The higher the score, the worse the athlete performed. Participants who were unable to maintain the testing position for a minimum of five seconds at the start, were assigned the highest possible score (i.e., 10) for that testing condition.[166,231] The BESS test has significant correlations with the force-platform sway measures, with intra-tester reliability coefficients from .87 to .97.[231]

3.3.4. Vestibular Ocular Motor Screening (VOMS)

The VOMS was developed to assess vestibular and ocular motor impairment via participant-reported symptom provocation following each assessment. The VOMS consists of brief assessments in the following five domains: 1) smooth pursuits; 2) horizontal and vertical saccades; 3) convergence; 4) horizontal and vertical vestibular ocular reflex (VOR); and 5) visual motion sensitivity (VMS). The athlete verbally rated changes in headache, dizziness, nausea, and fogginess symptoms compared to their pre-assessment state on a Likert scale of 0 (none) to 10 (severe) following each VOMS assessment, to determine if each assessment provokes symptoms. Convergence was assessed by both symptom report and measurement of the near point of convergence (NPC). NPC values were averaged across 3 trials. NPC values up to 5 cm are considered normal.[169] The VOMS took approximately 5 minutes to administer. VOMS has been previously reported to have moderate-high reliability, validity, and sensitivity when tested over multiple trials in concussed athletes.[169,188] (Appendix F).

VOMS: Smooth Pursuits. The participant and the examiner were seated, and the examiner held their fingertip 3 feet from the athlete. The athlete was instructed to maintain focus on the fingertip, as the examiner moved the fingertip smoothly in the horizontal direction 1.5 feet to the right and 1.5 feet to the left of midline. One repetition was completed when the fingertip moved back and forth to the starting position, and two repetitions were performed. The fingertip was moved at a rate requiring approximately two seconds to go fully from left to right and two seconds to go fully from right to left. The test was repeated with the fingertip smoothly and slowly moving in the vertical direction 1.5 ft. above and 1.5 ft. below midline for two complete repetitions up and down. Again, the fingertip was moved at a rate requiring approximately two seconds to move the eyes fully upward and two seconds to move fully downward. The examiner recorded the participant's headache, dizziness, nausea and fogginess ratings after the test.

VOMS: Horizontal Saccades. The examiner held two fingertips horizontally at a distance of 3 feet from the athlete, with 1.5 feet to the right and 1.5 feet to the left of midline, so that the participant gazed 30º to left and 30º to the right. The examiner instructed the participant to move their eyes as quickly as possible from fingertip to fingertip. One repetition was completed when the eyes move back and forth to the starting position, and 10 repetitions were performed. The examiner recorded the participant's headache, dizziness, nausea and fogginess ratings after the test.

VOMS: Vertical Saccades. The examiner repeated the test with two fingertips held vertically, 3 feet from the participant with 1.5 feet above and 1.5 feet below midline, so that the participant gazed 30º upward and 30º downward. The examiner instructed the participant to move their eyes as quickly as possible from fingertip to fingertip. One repetition was completed when the athletes' eyes moved up and down to the starting position, and 10 repetitions were performed. The examiner recorded the participant's headache, dizziness, nausea and fogginess ratings after the test.

VOMS: Convergence. The participant was seated and wearing corrective lenses (if needed). The examiner was seated in front of the participant and observed their eye movement during this test. The participant focused on a small target at arm's length and slowly brought the target towards the tip of their nose. The participant was instructed to stop the target when they saw two distinct images or when the examiner observed an outward deviation of one eye. Blurring of the image was ignored. The distance was recorded in centimeters and was measured from the target to the tip of the nose. This was repeated a total of three times, with measures recorded each time. The examiner recorded the participant's headache, dizziness, nausea and fogginess ratings after the test. This test was abnormal if the NPC was greater than or equal to six centimeters from the tip of the nose.

VOMS: Horizontal Vestibular-Ocular Reflex. The participant was asked to rotate their head horizontally, while maintaining focus on a target. The head was moved at an amplitude of 20° to each side and a metronome was used to ensure the speed of rotation, which was maintained at 180 beats/minute (one beat in each direction). One repetition was completed, when the head moved back and forth to the starting position, and 10 repetitions were performed. The examiner recorded the participant's headache, dizziness, nausea and fogginess ratings after the test.

VOMS: Vertical Vestibular-Ocular Reflex. This test was repeated with the participant moving their head vertically. The head was moved in an amplitude of 20° up and 20° down and a metronome was used to ensure the speed of movement, which was maintained at 180 beats/minute (one beat in each direction). One repetition was completed when the head moved up and down to the starting position, and 10 repetitions were performed. The examiner recorded the participant's headache, dizziness, nausea and fogginess ratings after the test.

VOMS Visual Motion Sensitivity. The athlete stood with their feet shoulder width apart, facing a busy area of the clinic. The examiner stood next to and slightly behind the participant, so that the participant was guarded, but the movement was performed freely. The athlete's arm was outstretched, and the participant was asked to focus on their thumb. While maintaining focus on their thumb, the participant rotates together as a unit, at an amplitude of 80° to the right and 80° to the left. A metronome was used to ensure the speed of rotation, which was maintained at 50 beats/min (one beat in each direction). One repetition is complete when the trunk rotates back and forth to the starting position, and five repetitions are performed. The examiner recorded the participant's headache, dizziness, nausea and fogginess ratings after the test.

3.3.5. Immediate Post-Concussion Assessment Cognitive Test (ImPACT)

To assess neurocognitive function, the online version of the ImPACT neurocognitive test battery was used for this study. The ImPACT test took approximately 20-25 minutes to complete and was designed to be administered on any laptop or desktop computer that had a color monitor. Additionally, it required an external mouse, reliable internet connection and must be connected to an external power source at the time of testing. There were specific requirements with regards to the test environment which included 1) the physical environment was quiet and free of noise, 2) all cell phones, music players, and other electronic devices were turned off, 3) the participant was not engaging in another activity or conversing with others, 4) seating arrangements allowed the athlete to sit comfortably with at least one seat between test takers when administered in a group setting, 5) the test was administered in an area that prevented from issues with a glare on the screen, and 6) under no circumstances participants were not allowed to complete testing at home without the supervision of a trained healthcare professional. The ImPACT neurocognitive test battery consisted of three sections that included the demographics, the Post-Concussion Symptom Scale (PCSS), and five composite components (i.e. verbal memory, visual memory, visual motor speed, impulse control, and reaction time composite scores), which was composed of six modules.[232] Computerized neurocognitive testing has been deemed a more objective measure for determining subtle cognitive changes associated with SRCs.[155,166] ImPACT has been reported to have moderate-high test-retest reliability, validity, and sensitivity and specificity.[150,156,233,234]

Word Memory: Module One. The first module evaluated attentional processes and verbal recognition memory, while using a word discrimination paradigm. Athletes were presented with 12 target words, twice to facilitate learning the list, which remained on the screen for 750 milliseconds at a time. Athletes were then tested for immediate recall by answering "yes" or "no", when presented a list of 24 words. At the end of the sixth module (approximately 20-25 minutes) athletes were presented with the same 24 words and asked to answer "yes" or "no." This test measured delayed memory of athletes and were scored based on a total percentage of correct answers.

Design Memory: Module Two. The second module measured attentional processes and visual recognition memory. This module also used a design discrimination paradigm. Athletes were presented with 12 target designs, twice and remain on the screen for 750 milliseconds at a time. Athletes were then tested for immediate recall by answering "yes" or "no", when presented 24 designs. At the end of the sixth module (approximately 20 minutes) athletes were presented with the same 24 designs and asked to answer "yes" or "no." This test measured delayed memory and was scored on total percentage correct.

X's and O's: Module Three. The third module evaluated visual working memory and visual processing/visual motor speed, by using a distractor task to interfere with memory rehearsal. The participant practiced the distracter task prior to the presentation of the memory task. Athletes were asked to perform a specific action if a blue square was presented or if a red circle was presented. The athlete right clicked if a red circle was presented and left clicked if a blue square was presented for the distractor task. Athletes were then presented a random screen of X's and O's with three yellow X's and/or O's. Athletes were presented the distractor test, followed by the same memory screen, without the yellow X's and/or O's. The athlete was asked to click on the three previously illuminated yellow X's and/or O's. The participant completed this module for a total of four times and received a score for correct identification of yellow X's and O's, reaction time for the distractor test and the number of errors on the distractor test.

Symbol Match: Module Four. The fourth module measured visual processing speed, learning, and memory. Athletes were presented nine common symbols on a screen. Directly under each symbol was a number from one to nine that corresponds respectively. Below this grid, a symbol was presented. The athlete was required to click on the matching number as quickly as possible, while at the same time remembering the number/symbol pairings. When an athlete clicked on the correct number, the number illuminated green. If the number was incorrect, it illuminated red. Following the completion of the 27 trials, the symbols disappear from the top grid. The test asked the athlete to click on the number that matched the symbol that was shown respectively. Athletes received an average reaction time score and a score for memory recall.

Color Match: Module Five. The fifth module evaluated a choice reaction task and measured impulse control/response inhibition. Athletes were required to click on the “red”, “green”, or “blue” word that was displayed on the screen, in the same color ink as the word. The participant was instructed to click on the box as quickly as possible, only if the word was presented in the matching ink. This task gave a reaction time score and an error score.

Three Letters: Module Six. The sixth module measured working memory and visual-motor response speed. First, the participant was able to practice a distracter task that consisted of 25 numbered buttons on a 5X5 grid. The participant was instructed to click as quickly as possible on the number buttons in backward order starting with 25. The position of the numbers on the grid were randomized after each trial to minimize practice effects. Immediately following display of the three letters, the numbered grid re-appeared, and the athlete was again instructed to click the numbered buttons in backward order. After 18 seconds, the numbered grid disappeared, and the athlete was asked to recall the three letters by typing them on the keyboard. This task gave a memory score and a score for the average number of correctly clicked numbers per trial from the distracter test. Five trials of this task were presented for this module.

3.3.6. Driving Simulation Tasks (STISIM Drive®)

The STISIM Drive® software was displayed on three fast-response HDTV displays, measuring approximately 43 inches horizontally. The three displays were connected to a triple display simulator chassis, with a SlipSense motion platform, stereo speaker system, and a fully reclining seat with adjustable seat sliders. This motion platform allows the driver to thoroughly feel tire traction and supplements the sensations from the quality force-feedback steering wheel. The force feedback steering wheel was responsive and had an adjustable angle of rotation from 270º-1080º. The steering wheel was approximately 30 centimeters in diameter with a genuine Alcantara grip, comprehensive driving controls and paddle shifters. Additionally, there was a three-pedal system, with highly progressive brake feel and a 7 speeds shifter for participants who drove a manual vehicle. Lastly, the PC computer that was utilized for the researcher contained an 8 GB DDR4 memory, 1TB HDD 120 GB SSD storage, Windows 10 home 64-bit operating system and an AMD Radeon RX 580 4 GB GDDR5 graphics processor (Figure 3).

Figure 3. *Driving Simulator Equipment.*

The STISIM Drive® software was a reliable and validated driving simulation system, specifically designed for medical and occupational therapy applications.[227,228] The STISIM Drive® software had been utilized in the literature for testing participants with mild traumatic brain injury (mTBIs), however the STISIM Drive® software has not been used with SRCs previously. This software has been engineered to facilitate the diagnosis, evaluation, treatment, and rehabilitation process of the needs of participants experiencing brain injury or impairment.

Additionally, it allowed the researcher to create a database that tracked the treatment, driving results (scenario results), and rehabilitation progress for each participant. Within the large portfolio of predesigned scenarios, this study used three primary tasks: 1) memory, planning, and navigation, 2) car following with DA, and 3) passing, gap judging and merging.[228]

The first task tested the participant's memory skills, by providing a math task prior to the driving scenario that the participant must remember to properly navigate through the scenario. The math task required the driver to pass slow moving traffic, while performing basic arithmetic. The participants were presented with 20 road signs that had 2-digit numbers on the signs and were asked to keep a running total of what the signs added/subtracted to during this task. In the middle and end of the task, the athletes were asked to state the current value of the road signs. Subjects were evaluated on memory, as well as any collisions or straying from one's lane while driving. This driving task took approximately 15 minutes.

The second task evaluated the participants' ability to drive a car, when exposed to a task that diverts their attention from driving. The test simulated driving in a residential area and a school zone. Hazards that appeared throughout the drive included pedestrians, cross traffic not stopped at unmarked intersections, vehicles backing out of driveways, parked cars along the roadway merging into traffic concurrently. The participants were evaluated on their ability to ignore diversions in attention and to not have any collisions or lane excursions. The athlete was presented with 23 different DA events and took approximately 7 minutes to complete.

Lastly, the third task evaluated a participant's passing, gap judgment, and merging driving skills. The driver was instructed to make a series of left turns against on-coming traffic, with a pedestrian crossing. The on-coming traffic had various sized gaps between the cars and the participant was required to determine when it was appropriate to execute the turn. This test took approximately 4 minutes to complete. The total time to complete all scenarios was approximately 25 minutes. The combination of these tasks was to evaluate the essential driving skill sets (memory, attention, and judgment) in the safety of a virtual environment allowing for a reliable method to determine the influence of SRCs on driving performance.

3.3.7. Motion Sickness Assessment Questionnaire (MSAQ)

Once participants completed all STISIM Drive® tasks, they were immediately administered the Motion Sickness Assessment Questionnaire (MSAQ). This questionnaire asks subjects to rate the severity of four types of symptoms: (1) gastrointestinal (sick to stomach, queasy, nauseated, may vomit), (2) central (faint-like, lightheaded, disoriented, dizzy, spinning), (3) peripheral (sweaty, clammy/cold sweat, hot/warm), and (4) sopite-related (annoyed/irritated, drowsy, tired/fatigued, uneasy). The measure requires participants to rate the degree to which they are experiencing 16 symptoms from 1 (not at all) to 9 (severe). An overall motion sickness score can then be calculated along with a score for each particular domain. The MSAQ has been shown to be a valid instrument (0.81-0.92) for the assessment of motion sickness.[235] To determine if patients had motion sickness due to the simulator instead of their concussion symptoms, the full return to participation stage MSAQ was compared to their within 72 hours and asymptomatic stage. (Appendix G)

3.4. Procedures

Test-Retest Reliability of the STISIM Drive® Software

A total of 59 healthy college-aged students reported to the Spartan Motorsport Performance Lab (SMPL) at Michigan State University, where the car simulator is housed. Within the first testing session, participants were provided with written informed consent, as well as screened for inclusionary/exclusionary criteria prior to enrollment in the study. After it was determined that a student qualified for the study, participants completed demographic and driving history questionnaires. Once the forms were completed, students were administered the STISIM Drive® software and the MSAQ immediately following the driving tasks. Before completing the STISIM Drive® software driving tasks, the participant performed a five-minute practice test to get acquainted with the driving simulator to reduce simulator discomfort. After one week, participants would report back to the laboratory to complete the second driving session. In the second driving session, they completed only the STISIM Drive® tasks and MSAQ. All paperwork and driving simulation tasks were administered by the principle investigator and trained research assistants. All forms that were recorded were either locked in a file cabinet or on a password protected computer. Additionally, this study involved minimal to no risk to the participant. No individual methodological element was new, untested, or of questionable safety for the health and general well-being of humans. Total testing time for each session was approximately 20-30 minutes.

Simulated Driving Performance in Concussed and Non-Concussed Athletes

A total of 40 concussed and non-concussed match control athletes, reported to the SMPL at Michigan State University, where the car simulator is housed. Participants or parents/child were provided with written informed consent and/or assent, as well as screened for inclusionary/exclusionary criteria prior to enrollment in the study. After it was determined that an athlete qualified for the study, participants completed demographic and driving history questionnaires. Once the forms were completed, athletes were administered the STISIM Drive® tasks, a motion sickness assessment questionnaire, and a multi-faceted approach to SRC management which included the following measures 1) SCAT5, 2) ImPACT, and 3) VOMS. Before completing the STISIM Drive® software driving tasks, the participant performed a five-minute practice test to get acquainted with the driving simulator to reduce simulator discomfort. All concussed and matched control athletes were randomly administered the aforementioned tests, through a random number generator, within 72 hours of a sustained SRC (session 1), when they were asymptomatic (session 2), and when they have completed their step-wise return to participation and cleared without restrictions by a healthcare professional (session 3).

All post-concussion tests were administered by the principle investigator and trained research assistants. All forms that were recorded were either locked in a file cabinet or on a password protected computer. This study involved minimal to no risk to the participant. All procedures, techniques, equipment, and measures that were utilized in this study were routinely used in educational and research settings involving humans. No individual methodological element was new, untested, or of questionable safety for the health and general well-being of humans. The driving simulation tasks provided a safe and controlled experience in which errors could be made without cost to life, health, or property.[236,237] In addition, all return-to-play decisions were determined by each concussed athlete's healthcare provider (i.e., MD/DO/PA/ATC). Total testing time for each session was approximately 1.5 hours.

3.5. Data Analysis

Descriptive statistics were performed on all independent and dependent variables, on all participants. Additionally, 2-way mixed intraclass correlation coefficients (ICC) (purpose one), multiple multivariate analysis of variance (purpose two), and separate Spearman's rho correlation coefficients (purpose three) were calculated. Additionally, separate Mann-Whitney U tests were used to examine group differences in driving experience, accident and ticket history, and pre-existing conditions. The statistical significance level was set at an *a-priori* alpha level *p*

< 0.05 for all analyses. Data were analyzed using the Statistical Package for the Social Sciences (24.0 version) software.

3.5.1. Hypotheses

H1a. The STISIM Drive® software will reflect acceptable ICC values (0.75).

A 2-way mixed ICCs for STISIM Drive® outcome variables (i.e. road lane excursions, centerline crossings, car collisions, pedestrian collisions, stop sign tickets, speeding tickets, turn signal usage and DA) were calculated between time points one and two, with one week in between each session. ICCs range from zero to one, with values closed to one indicate less error variance and stronger reliability. This study interpreted test-retest reliability for clinical use as <0.50, between 0.50-0.75, between 0.75-0.90, and >0.90 as indicative of poor, moderate, good, and excellent reliability, respectively.[238]

H2a: Concussed high school and collegiate athletes will perform more road lane excursions, centerline crossings, car collisions, pedestrian collisions, speeding tickets, stop sign tickets, and have less turn signal usage and DA on the simulated driving tasks within 72 hours and asymptomatic stages, compared to matched non-concussed high school and collegiate athletes.

H2b: There will be no differences on road lane excursions, centerline crossings, car collisions, pedestrian collisions, stop sign tickets, speeding tickets, turn signal usage and DA on the simulated driving tasks at the return to full participation session between concussed and matched non-concussed high school and collegiate athletes.

Multiple 2 experimental group (concussed, non-concussed controls) X 3 clinical indicators of the SRC recovery process (within 72 hours, asymptomatic, return to full participation) repeated measures multivariate analysis of variance (MANOVAs) were performed to determine if there were differences on simulated driving performance (i.e. road lane excursions, centerline crossings, car collisions, pedestrian collisions, stop sign tickets, speeding tickets, turn signal usage and DA) between and within concussed and non-concussed high school and collegiate athletes.

H3: There will be a strong association between simulated driving performance measures and concussion measures (i.e. symptoms, neurocognitive, balance and vestibular/ocular motor) at all clinical indicators of the SRC recovery (i.e. within 72 hours, asymptomatic, return to participation) for the concussed group.

Separate Spearman's rho correlation coefficients were calculated to explore the relationship between the SRC concussion measures (i.e. symptoms [symptoms total, symptoms severity], neurocognitive [verbal memory, visual memory, visual motor speed, impulse control, reaction time], balance [firm surface total errors, foam surface total errors], and vestibular/ocular motor [smooth pursuits, horizontal and vertical saccades, convergence, horizontal and vertical vestibular ocular reflex, visual motion sensitivity]) and simulated driving performance variables (i.e. road lane excursions, centerline crossings, car collisions, pedestrian collisions, stop sign tickets, speeding tickets, turn signal usage and DA) for the concussed group, at each clinical indicator time session (i.e. within 72 hours, asymptomatic, return to full participation). This study interpreted correlations for clinical use as 0.0-0.3, between 0.3-0.5, between 0.5-0.7, between 0.7-0.9 and 0.9-1.0 as indicative of negligible, weak, moderate, strong, and very strong positive or negative correlations, respectively.[239]

CHAPTER 4

RESULTS

4.1. Demographic Information

Test-Retest Reliability of the STISIM Drive® Software

Participant characteristics are provided in Table 3. A total of 59 heathy, college-aged students met the inclusion criteria and voluntarily participated in the current study. In addition, there was a 100% retention rate, in which all participants completed both sessions of the test-retest study. Two participants were excluded from the study based on illicit drug usage at the time of the session and invalid driver's license. The sample included 19 male (32.2%) and 40 (67.8%) female college-aged students. Participants had an average age of 20.8 ± 1.2 years, height of 1.7±0.1m, and weight of 69.3±13.5kgs. The majority of participants reported that they were Non-Hispanic White (n=47, 79.6%) , followed by Asian (n=3, 5.1%) and Non-Hispanic Black/African American (n=3, 5.1%). Additionally, a majority of the sample were senior students (n=31, 52.5%), followed by junior students (n=20, 33.9%), and freshman (n=6, 10.2%), within the Department of Kinesiology and had an average GPA of 3.6±0.4. Lastly, the students reported the following diagnosed conditions, ADD/ADHD (n=1, 1.7%), depression (n=4, 6.8%), anxiety (n=1, 1.7%), migraines (n=3, 5.1%), previous concussion (n=17, 28.8%). Participant characteristics related to pre-existing conditions are provided in Table 4. Separate Mann-Whitney U tests were conducted to examine if pre-existing conditions should be controlled for in the inferential statistical analysis. ADD/ADHD (p=0.48), depression (p=0.47), anxiety (p=0.45), previous concussion (p=0.36), and migraines (p=0.32) were not shown to be significant and was not controlled for analysis.

Simulated Driving Performance in Concussed and Non-Concussed Athletes

A total of 38 (19 concussed, 19 match controls) high school (n=6, 15.8%), club (n=16, 42.1%) and collegiate (n=16, 42.1%)) athletes met the inclusion criteria and voluntarily participated in the study. In addition, there was a 100% retention rate, in which all participants completed all three-time sessions of the study. The sample included 30 male (78.9%) and 8 female (21.2%) athletes. Participants had an average age of 20.0±1.6 years, height of 1.8±0.1m and weight of 79.1±14.0kgs. The majority of participants reported that they were Non-Hispanic White (n=32, 84.3%), followed by Non-Hispanic Black/African American (n=3, 7.9%). In addition, approximately a quarter of the sample were from the following sports, football (n=10, 26.3%), followed by Rugby (n=4, 10.5%), ROTC (n=4, 10.5%), and Quidditch (n=4, 10.5%) (Table 5). Participant characteristics are provided in Tables 3 and 5. Lastly, the athletes reported the following diagnosed conditions, ADD/ADHD (n=3, 7.9%), depression (n=2, 5.3%), learning disability/dyslexia (n=1, 2.6%), and previous concussion (n=17, 44.7%). Participant characteristics related to pre-existing conditions are provided in Table 4. While examining the concussed athletes' demographics relating to their concussion, most concussions were sustained in competition (n=11, 57.9%) and their mechanism of injury was by making contact with the ground (n=7, 36.9%). In addition, concussed athletes were seen by the research investigator within 48.3±17.6 hours of the 72-hour testing session, 20.4±13.6 hours of the asymptomatic session, and 13.7±14.8 hours of the RTP session. Lastly, concussed athletes took 12.2±15.1 days before becoming asymptomatic, and 18.3±20.1 days before RTP. Participant characteristics related to their respective sport are provided in Table 6. Separate Mann-Whitney U tests were conducted to examine if pre-existing conditions should be controlled for in the inferential statistical analysis. ADD/ADHD (p=0.08), depression (p=0.15), previous concussion (p=0.75), and learning disability/dyslexia (*p*=0.32), were not shown to be significant and was not controlled for analysis.

Table 3. *Participant Demographics for Test-Retest Students, Concussed and Non-Concussed Athletes.*

	Test-Retest Students *(n = 59)* *n (%)*	Concussed Athletes *(n = 19)* *n (%)*	Non-Concussed Athletes *(n = 19)* *n (%)*
Age (years), (*M* ± *SD)*	20.8±1.2	20.0±1.7	20.0±1.7
Sex			
Male	19 (32.2 %)	15 (78.9%)	15 (78.9%)
Female	40 (67.8 %)	4 (21.1%)	4 (21.1%)
Height (m), (*M* ± *SD)*	1.7±0.1	1.7±0.1	1.8±0.1
Weight (kg), (*M* ± *SD)*	69.3±13.5	81.7±14.7	76.5±13.1
Race			
Asian	3 (5.1%)	1 (5.3%)	-
Hispanic White	2 (3.4%)	1 (5.3%)	-
Middle Eastern	2 (3.4%)	-	1 (5.3%)
Non-Hispanic Black/ African American	3 (5.1%)	2 (10.5%)	1 (5.3%)
Non-Hispanic White	47 (79.6%)	15 (78.9%)	17 (89.5%)
Mixed Race	2 (3.4%)	-	-
Handedness			
Right	50 (84.7%)	19 (100.0%)	17 (89.5%)
Left	7 (11.9%)	-	2 (10.5%)
Both	2 (3.4%)	-	-
Contact or Glasses			
Yes	30 (50.8%)	8 (42.1%)	9 (47.4%)
No	29 (49.2%)	11 (57.9%)	10 (52.6%)
Academic Year			
Junior (HS)	-	1 (5.3%)	1 (5.3%)
Senior (HS)	-	2 (10.5%)	2 (10.5%)
Freshman	6 (10.2%)	1 (5.3%)	2 (10.5%)
Sophomore	2 (3.4%)	3 (15.8%)	1 (5.3%)
Junior	20 (33.9%)	5 (26.3%)	9 (47.4%)
Senior	31 (52.5%)	7 (36.8%)	4 (21.1%)

Table 3. *(cont'd)*

GPA (4.0), (*M* ± *SD)*	3.6±0.4	3.3±0.4	3.3±0.4

Table 4. *Participant Demographics for Pre-Existing Conditions for Test-Retest Students, Concussed and Non-Concussed Athletes.*

	Test-Retest Students *(n = 59)* *n (%)*	Concussed Athletes *(n = 19)* *n (%)*	Non-Concussed Athletes *(n = 19)* *n (%)*
Previous Concussion			
0	42 (71.2%)	10 (52.6%)	11 (57.9%)
1	7 (11.9%)	5 (26.3%)	5 (26.3%)
2	6 (10.2%)	1 (5.3%)	3 (15.8%)
>3	4 (6.7%)	3 (15.8%)	-
History of Headaches/Migraines			
Yes	3 (5.1%)	-	-
No	56 (94.9%)	19 (100.0%)	19 (100.0%)
Learning Disability/Dyslexia			
Yes	-	-	1 (5.3%)
No	59 (100.0%)	19 (100.0%)	18 (94.7%)
ADD/ADHD			
Yes	1 (1.7%)	3 (15.8%)	-
No	58 (98.3%)	16 (84.2%)	19 (100.0%)
Depression			
Yes	4 (6.8%)	2 (10.5%)	-
No	55 (93.2%)	17 (89.5%)	19 (100.0%)
Anxiety			
Yes	1 (1.7%)	-	-
No	58 (98.3%)	19 (100.0%)	19 (100.0%)

Table 5. *Participant Demographics for Sport Participation.*

	Concussed Athletes *(n = 19)* *n (%)*	Non-Concussed Athletes *(n = 19)* *n (%)*	Total Athletes *(n = 38)* *n (%)*

Table 5. *(cont'd)*

Level of Participation	3 (15.8%)	3 (15.8%)	6 (15.8%)
High School	8 (42.1%)	8 (42.1%)	16 (42.1%)
Club	8 (42.1%)	8 (42.1%)	16 (42.1%)
College			
Sport			
Baseball	1 (5.3%)	1 (5.3%)	2 (5.3%)
Field Hockey	1 (5.3%)	1 (5.3%)	2 (5.3%)
Football	5 (26.3%)	5 (26.3%)	10 (26.3%)
Ice Skating	1 (5.3%)	1 (5.3%)	2 (5.3%)
Quidditch	2 (10.5%)	2 (10.5%)	4 (10.5%)
ROTC	2 (10.5%)	2 (10.5%)	4 (10.5%)
Rugby	2 (10.5%)	2 (10.5%)	4 (10.5%)
Soccer	1 (5.3%)	1 (5.3%)	2 (5.3%)
Swimming	1 (5.3%)	1 (5.3%)	2 (5.3%)
Volleyball	1 (5.3%)	1 (5.3%)	2 (5.3%)
Wrestling	2 (10.5%)	2 (10.5%)	4 (10.5%)

Table 6. *Sport Setting and Mechanism of Injury for Athlete's who sustained a SRC.*

	Concussed Athletes *(n = 19)* *n (%)*
Sport Setting	
Club Competition	5 (26.3%)
Club Practice	3 (15.8%)
High School Practice	3 (15.8%)
NCAA Competition	6 (31.6%)
NCAA Practice	2 (10.5%)
Play	
Offense	13 (68.4%)
Defense	6 (31.6%)
Mechanism of Injury	
Collision with Opponent	2 (10.5%)
Collision with Teammate	3 (15.8%)
Contact with Barrier/Object/Ball	5 (26.3%)
Contact with Ground	7 (36.9%)
Tackled and Opponent	2 (10.5%)

4.2. Driving Demographics

Test-Retest Reliability of the STISIM Drive® Software

Of the 59 heathy, college-aged students, the sample reported 4.9±1.4 years of driving experience, 5.1±2.2 days per week driving, and 4.5±4.1 hours per week driving. A majority of the students drove a sedan vehicle (n=27, 45.8%), followed by a SUV (n=25, 42.4%) and typically drove in a suburban area (n=42, 71.2%). Additionally, a majority of the students reported using their cell phone to make/take calls (n=37, 62.7%) and did not read or type text messages (n=49, 83.1%) while driving. In the past three years, the majority of students reported receiving no tickets (n= 49, 83.1%) with two thirds reporting no accidents (n=40, 67.8%). Furthermore, a majority of participants stated that they always (n=31, 52.5%) and almost always (n= 26, 44.1%) use their blinker, are not an aggressive driver (n=32, 54.2%) and consider their quality of driving to be good (n=46, 78.0%). Driving characteristics are provided in Table 7. Separate Mann-Whitney U tests were conducted to examine if years of driving experience, accident and ticket history should be controlled for in the inferential statistical analysis. Years of driving experience (p=0.09), accident (p=0.33), and ticket history (p=0.06), were not shown to be significant and was not controlled for analysis.

Simulated Driving Performance in Concussed and Non-Concussed Athletes

Of the 38 athletes, the sample reported 4.2±1.7 years of driving experience, 5.7±1.9 days per week driving, and 5.2±4.2 hours per week driving. A majority of the athletes drove a sedan vehicle (n=17, 44.7%), followed by a SUV (n=10, 26.3%) and typically drove in a suburban area (n=20, 52.6%). Additionally, a majority of the athletes reported using their cell phone to make/take calls (n=21, 55.3%), and did not read or text messages (n=27, 71.1%) while driving. In the past three years, athletes reported receiving no tickets (n=24, 63.2%) and no accidents (n=30, 78.9%). Furthermore, a majority of participants stated that they always (n=19, 50.0%) and almost always (n=18, 47.4%) use their blinker, are not an aggressive driver (n=35, 92.1%) and consider their quality of driving to be considered good (n=21, 55.3%). Driving characteristics are provided in Table 7. Separate Mann-Whitney U tests were conducted to examine if years of driving experience, accident and ticket history should be controlled for in the inferential statistical analysis. Years of driving experience (p=0.38), accident (p=0.88), and ticket history (p=0.20), were not shown to be significant and was not controlled for analysis.

Table 7. *Driving Demographics for Test-Retest Students, Concussed and Non-Concussed Athletes*

	Test-Retest Students *(n = 59)* *n (%)*	Concussed Athletes *(n = 19)* *n (%)*	Non-Concussed Athletes *(n = 19)* *n (%)*
Years of Driving Experience, *(M ± SD)*	4.9±1.4	4.4±1.6	3.9±1.7
Days Driving of the Week, (*M ± SD)*	5.1±2.2	5.2±2.1	6.2±1.4
Hours Driving of the Week, (*M ± SD)*	4.5±4.1	4.7±4.9	5.7±3.5
Type of Vehicle			
Coupe	1 (1.7%)	1 (5.3%)	2 (10.5%)
Crossover	1 (1.7%)	-	-
Hatchback	3 (5.1%)	2 (10.5%)	3 (15.8%)
Moped	-	1 (5.3%)	-
Pickup	1 (1.7%)	-	1 (5.3%)
Sedan	27 (45.8%)	9 (47.4%)	8 (42.1%)
SUV	25 (42.4%)	6 (31.6%)	4 (21.1%)
Wagon	1 (1.7%)	-	1 (5.3%)
Areas Driving			
Rural	4 (6.8%)	-	2 (10.5%)
Suburban	42 (71.2%)	12 (63.2%)	8 (42.1%)
Urban	13 (22.0%)	7 (36.8%)	9 (47.4%)
Average Speed on Main Roads (35mph), *(M ± SD)*	42.3±6.6	40.5±9.1	39.1±8.4

Table 7. *(cont'd)*

Average Speed on Freeways (70mph), (*M* ± *SD*)	75.7±4.7	74.9±2.9	76.0±3.6
Make/Take Calls			
Yes	22 (37.3%)	11 (57.9%)	10 (52.6%)
No	37 (62.7%)	8 (42.1%)	9 (47.4%)
Average Minutes on Phone, (*M* ± *SD*)	8.0±5.7	6.9±5.1	7.3±7.1
Speed of Driving, While on the Phone			
Faster	4 (10.8%)	-	1 (5.3%)
Same	15 (40.5%)	6 (31.6)	7 (36.8%)
Slower	18 (48.7%)	5(26.3%)	2 (10.5%)
Use a Headset/Bluetooth			
Yes	33 (55.9%)	3 (15.8%)	7 (36.8%)
No	26 (44.1%)	16 (84.2%)	12 (63.2%)
Read/Type Text Messages			
Yes	10 (16.9%)	6 (31.6%)	5 (26.3%)
No	49 (83.1%)	13 (68.4%)	14 (73.7%)
Average Texts Read on Phone, (*M* ± *SD*)	4.5±3.9	3.3±3.6	3.8±3.8
Average Texts Typed on Phone, (*M* ± *SD*)	3.0±2.8	6.5±7.4	3.0±3.9
Speed of Driving, While on the Phone			
Same	3 (30.0%)	1 (5.3%)	2 (10.5%)
Slower	7 (70.0%)	5 (26.3%)	3 (15.8%)
Tickets in the Past 3 Years			
0	49 (83.1%)	12 (63.2%)	12 (63.2%)
1	5 (8.5%)	6 (31.6%)	6 (31.6%)
2	5 (8.5%)	1 (5.3%)	1 (5.3%)
Pulled Over, But Did Not Receive a Ticket in the Past 3 Years			
0	33 (55.9%)	5 (26.3%)	10 (52.6%)
1	12 (20.3%)	6 (31.6%)	4 (21.1%)
2	13 (22.0%)	5 (26.3%)	4 (21.1%)

Table 7. *(cont'd)*

3	1 (1.7%)	1 (5.3%)	1 (5.3%)
6	-	1 (5.3%)	-
10	-	1 (5.3%)	-
Accidents in the Past 3 Years			
0	40 (67.8%)	14 (73.7%)	16 (84.2%)
1	18 (30.5%)	3 (15.8%)	3 (15.8%)
2	1 (1.7%)	2 (10.5%)	-
Who's at Fault from Accident			
You	12 (63.2%)	2 (10.5%)	2 (10.5%)
Other Driver	6 (31.6%)	3 (15.8%)	1 (5.3%)
Both	1 (5.2%)	-	-
DUI in the Past 3 Years			
No	59 (100.0%)	19 (100.0%)	18 (94.7%)
Yes	-	-	1 (5.3%)
Blinker Usage			
Always	31 (52.5%)	8 (42.1%)	11 (57.9%)
Almost Always	26 (44.1%)	10 (52.6%)	8 (42.1%)
Sometimes	2 (3.4%)	1 (5.3%)	-
Advance Driving			
Yes	3 (5.1%)	2 (10.5%)	1 (5.3%)
No	56 (94.9%)	17 (89.5%)	18 (94.7%)
Aggressive Driver			
Yes	3 (5.1%)	2 (10.5%)	-
No	32 (54.2%)	12 (63.2%)	13 (68.4%)
Sometimes	24 (40.7%)	5 (26.3%)	6 (31.6%)
Seatbelt Usage			
Yes	59 (100.0%)	19 (100.0%)	19 (100.0%)
Average Speed Compared to Traffic			
About the Same	36 (61.0%)	6 (31.6%)	7 (36.8%)
Somewhat Faster	20 (33.9%)	13 (68.4%)	12 (63.2%)
Somewhat Slower	3 (5.1%)	-	-
Quality of Driving			
Excellent	7 (11.9%)	8 (42.1%)	6 (31.6%)
Good	46 (78.0%)	9 (47.4%)	12 (63.2%)
Average	6 (10.2%)	2 (10.5%)	1 (5.3%)

Table 7. *(cont'd)*

Drive Alone			
Yes	34 (57.6%)	13 (68.4%)	12 (63.2%)
No	2 (3.4%)	1 (5.3%)	1 (5.3%)
Sometimes	23 (39.0%)	5 (26.3%)	6 (31.6%)

4.3. Evaluation of Hypotheses

Test-Retest Reliability: Memory, Planning, and Navigation Scenario

Spearman's rho correlation coefficients between time point one and time point two ranged from 0.35 to 0.77. ICCs reflected higher reliability than Spearman's ρ across all measures. In our entire sample, the ICC revealed poor to good reliability (0.49-0.86). Poor performance on turn signal usage showed the most stability (ICC=0.86; [95% confidence intervals = 0.76, 0.91]), followed by good performance of turn signal usage (ICC=0.80; [95% confidence intervals=0.66, 0.88]) with good reliability. Missed turn signal usage (ICC=0.74), road edge excursions (ICC=0.63), centerline crossings (ICC=0.59), and speeding tickets (ICC=0.56) displayed moderate reliability. Over the speed limit percentage (ICC=0.49) reflected poor reliability, however it was approaching moderate reliability. Unbiased estimate of reliabilities were also consistent with ICCs. Car collisions were not recorded in the analysis, due to no one hitting another car in the scenario. All measures of simulated driving performance, except for good and poor performance of turn signal usage, showed a significant improvement between the two assessments (Table 8).

Table 8. *One Week Test-Retest Reliability for Memory, Planning, and Navigation Scenario*

Variable	Time 1	Time 2	ρ	ICC	ICC 95% CI Lower	ICC 95% CI Upper	UER	*p*
Turn Signal: Good Performance								
M	16.6	13.6	0.65	0.80	0.66	0.88	0.81	<0.001
(SD)	6.7	8.1						

Table 8. *(cont'd)*

Turn Signal: Poor Performance								
M	10.6	14.8	0.77	0.86	0.76	0.91	0.86	<0.001
(SD)	7.3	8.8						
Turn Signal: Missed Performance								
M	2.6	1.8	0.48	0.74	0.56	0.84	0.74	<0.001
(SD)	4.4	4.4						
Speeding Tickets								
M	2.3	1.1	0.35	0.56	0.25	0.74	0.58	0.001
(SD)	2.5	1.8						
Centerline Crossings								
M	-0.6	-0.4	0.41	0.59	0.32	0.76	0.60	<0.001
(SD)	0.9	1.0						
Road Edge Excursions								
M	0.7	0.3	0.55	0.63	0.37	0.78	0.71	<0.001
(SD)	1.6	0.8						
Over Speed Limit Percentage								
M	2.1	1.0	0.36	0.49	0.14	0.70	0.51	0.006
(SD)	3.0	2.1						

ICC = Intraclass correlation coefficient
UER = Unbiased estimate of reliability
df = 7; Bonferroni corrected alpha $p < 0.007$

Test-Retest Reliability: Car Following with DA Scenario

Spearman's rho correlation coefficients between time point one and time point two ranged from 0.09 to 0.40. ICCs reflected higher reliability than Spearman's ρ across all measures. Additionally, the ICC revealed poor reliability on all measures (0.25-0.65). All variables were below the ICC=0.75 for acceptable reliability. Stop sign tickets (ICC=0.65) and DA response time (ICC=0.55) had moderate reliability, while all other variables had poor reliability. Unbiased estimate of reliabilities were also consistent with ICCs. Road lane excursions, car collisions and pedestrian collisions were not recorded in the analysis, due to no one performing a road lane excursion, or hitting another car or pedestrian in the scenario. All measures of simulated driving performance, except for DA response time and stop sign tickets, did not show a significant improvement between the two assessments (Table 9).

Table 9. *One Week Test-Retest Reliability for Car Following with DA Scenario*

Variable	Time 1	Time 2	ρ	ICC	ICC 95% CI		UER	*p*
					Lower	Upper		
DA Total Response Time								
M	1.9	1.4	0.40	0.55	0.25	0.74	0.58	0.001
(SD)	0.5	0.4						
Speeding Tickets								
M	0.7	0.5	0.25	0.45	0.07	0.67	0.50	0.013
(SD)	1.8	1.0						
Stop Sign Tickets								
M	2.2	1.8	0.41	0.65	0.42	0.79	0.65	<0.001
(SD)	1.6	1.6						
Correct DA Response								
M	20.3	21.5	0.34	0.45	0.08	0.68	0.50	0.011
(SD)	2.5	1.5						
Incorrect DA Response								
M	0.1	0.1	0.09	0.25	-0.26	0.55	0.26	0.138
(SD)	0.4	0.3						

Table 9. *(cont'd)*

Missed DA Response								
M	2.6	1.3	0.33	0.47	0.11	0.69	0.52	0.008
(SD)	2.4	1.4						
Over Speed Limit Percentage								
M	0.6	0.5	0.27	0.35	-0.10	0.61	0.37	0.055
(SD)	1.7	1.1						

ICC = Intraclass correlation coefficient
UER = Unbiased estimate of reliability
df = 7; Bonferroni corrected alpha $p < 0.007$

Test-Retest Reliability: Passing, Gap Judging and Merging Scenario

Spearman's rho correlation coefficients between time point one and time point two ranged from 0.17 to 0.32. ICCs reflected higher reliability than Spearman's ρ across all measures. Additionally, all ICCs on all measures revealed poor reliability (0.25-0.44) and were below the ICC=0.75 for acceptable reliability. Unbiased estimate of reliabilities were also consistent with ICCs. Road lane excursions, and car and pedestrian collisions were not recorded in the analysis, due to no one performing a road lane excursion, or hitting another car or pedestrian in the scenario. All measures of simulated driving performance did not show a significant improvement between the two assessments (Table 10).

Table 10. *One Week Test-Retest Reliability for Passing, Gap Judging and Merging Scenario*

Variable	Time 1	Time 2	ρ	ICC	ICC 95% CI		UER	*p*
					Lower	Upper		
Turn Signal: Good Performance								
M	3.7	3.5	0.17	0.25	-0.26	0.55	0.26	0.137
(SD)	0.7	0.5						

Table 10. *(cont'd)*

Turn Signal: Poor Performance								
M	0.4	0.6	0.25	0.36	-0.08	0.62	0.36	0.048
(SD)	0.5	0.6						
Turn Signal: Missed Performance								
M	0.4	0.3	0.21	0.34	-0.11	0.61	0.36	0.059
(SD)	0.8	0.6						
Speeding Tickets								
M	0.3	0.1	0.23	0.35	-0.10	0.61	0.38	0.053
(SD)	0.6	0.4						
Over Speed Limit Percentage								
M	0.4	0.2	0.32	0.44	0.05	0.67	0.50	0.015
(SD)	1.1	0.6						

ICC = Intraclass correlation coefficient
UER = Unbiased estimate of reliability
df = 5; Bonferroni corrected alpha $p < 0.010$

4.3.2. Simulated Driving Performance in Concussed and Non-Concussed Athletes: Memory, Planning, and Navigation Scenario

A 2 (group) X 3 (time) repeated measures MANOVA was performed to assess differences on simulated driving performance (i.e. road lane excursions, centerline crossings, car collisions, speeding tickets, turn signal usage, over speed limit percentage) between concussed and non-concussed high school and collegiate athletes, over the 3 previously described time points. There was no group ($F_{1,28}$=1.56, p=0.73) main effect or group-by-time ($F_{1,20}$=1.56, p=0.79) interaction for simulated driving performance, however there was a significant difference for the time main effect ($F_{1,20}$=1.56, p<0.001) (Table 11). When concussed and non-concussed athletes were pooled, there was a time main effect for conducting good ($F_{1,2}$=1.56, *p*<0.001), poor ($F_{1,2}$=1.56, *p*<0.001) and missed ($F_{1,2}$=1.56, *p*=0.04) turn signal usage and centerline crossings ($F_{1,2}$=1.56, *p*=0.05), while all other driving measures were non-significant for a time main effect. For good performance, participants had less, good turn signal usage from the 72-hour session to the asymptomatic session and from the 72-hour session to the RTP session, while no differences were seen from the asymptomatic session to the RTP session. For poor performance, participants conducted more poor turn signal usage from the 72-hour session to the asymptomatic session and from the 72-hour session to the RTP session, while no differences were seen between the asymptomatic session to the RTP session. For missed performance of turn signal usage, participants had less missed turn signal usage from the 72-hour session to the RTP session, but no differences were seen between the 72-hour session and the asymptomatic session and the asymptomatic session to the RTP session. Lastly for centerline crossing, participants conducted more centerline crossings from the 72-hour session to the asymptomatic session, but no differences were seen between the 72-hour session and the RTP session and the asymptomatic session and the RTP session (Table 12).

Table 11. *Descriptives of Simulated Driving Performance in Memory, Planning, and Navigation Scenario*

	Concussed Athletes			Non-Concussed Athletes		
	Within 72 hours	Asymptomatic	RTP	Within 72 hours	Asymptomatic	RTP
Turn Signal: Good Performance						
M	10.0	6.9	6.0	11.2	7.3	7.0
(SD)	6.1	6.4	5.9	7.8	7.7	8.6
Turn Signal: Poor Performance						
M	16.6	22.6	23.8	15.0	20.0	22.0
(SD)	8.0	7.0	6.3	9.6	10.3	9.9

Table 11. *(cont'd)*

Turn Signal: Missed Performance						
M	3.6	1.9	1.4	4.2	3.8	2.4
(SD)	4.5	2.7	1.8	6.8	6.8	4.8
Car Collisions						
M	0.1	0.0	0.0	0.0	0.0	0.1
(SD)	0.2	0.0	0.0	0.0	0.0	0.2
Speeding Tickets						
M	8.7	7.2	6.6	6.5	5.2	7.0
(SD)	4.8	6.0	5.3	5.2	5.1	7.6
Centerline Crossings						
M	-0.2	0.5	-0.1	-0.7	-0.1	-0.1
(SD)	1.5	1.3	0.9	0.9	1.0	0.6
Road Edge Excursions						
M	0.4	0.2	0.2	0.4	0.1	0.1
(SD)	1.2	0.4	0.4	0.7	0.3	0.5

Table 12. *Descriptives of Simulated Driving Performance in Memory, Planning, and Navigation Scenario by Time (M ± SD)*

		All Participants *n=38*	
	Within 72 hours	Asymptomatic	RTP
Turn Signal: Good Performance	10.6±7.1	7.1±1.2	6.5±1.2
Turn Signal: Poor Performance	15.8±1.4	21.3±1.4	22.9±1.4
Turn Signal: Missed Performance	3.9±0.9	2.9±0.8	1.9±0.6
Car Collisions	0.0±0.3	0.0±0.0	0.03±0.3
Speeding Tickets	7.6±0.8	6.2±0.9	6.8±1.1

Table 12. *(cont'd)*

Centerline Crossings	-0.5±0.2	0.2±0.2	-0.1±0.1
Road Edge Excursions	0.4±0.2	0.2±0.1	0.1±0.1
Over Speed Limit Percentage	19.7±3.6	20.6±4.7	19.6±4.1

Simulated Driving Performance in Concussed and Non-Concussed Athletes: Car Following with DA Scenario

A 2 (group) X 3 (time) repeated measures MANOVA was performed to assess differences in simulated driving performance (i.e. DA total response time, car collisions, pedestrian collisions, speeding tickets, stop sign tickets, road edge excursions, correct DA responses, incorrect DA responses, missed DA responses, over speed limit percentage, pedestrian collision response time, car collision response time) between and within concussed and non-concussed high school and collegiate athletes, over the 3 previously described time points. There was no group ($F_{1,27}$=1.48, p=0.20) main effect or group-by-time ($F_{1,18}$=1.09, p=0.43) interaction for simulated driving performance. Even though group was non-significant, it is important to note that four concussed participants had five pedestrian collisions during this particular scenario, while non-concussed athletes had zero pedestrian collisions, over the critical indicators of SRC recovery. This was furthered examined in the between subjects' univariate and was found to be significant (p=0.05) (Figure 4).

In addition, there was also a significant main effect for time ($F_{1,18}$=6.40, p<0.001) (Table 13). When concussed and non-concussed athletes were pooled, there was a time main effect in DA total response time ($F_{1,2}$=1.56, p<0.001), speeding tickets ($F_{1,2}$=6.55, p<0.001), stop sign tickets ($F_{1,2}$=9.97, p<0.001), correct DA responses ($F_{1,2}$=15.88, p<0.001), incorrect DA responses

($F_{1,2}$=3.82, p=0.04), missed DA responses ($F_{1,2}$=14.02, p<0.001), over speed limit percentage ($F_{1,2}$=4.46, p=0.02), pedestrian collisions response time ($F_{1,2}$=21.11, p<0.001), and car collision response time ($F_{1,2}$=10.37, p<0.001, while all other driving measures were non-significant for a time main effect. For DA total response time, participants performed faster from their 72-hour session to their asymptomatic session, their 72-hour session to their RTP session, and their asymptomatic session to their RTP session. For speeding tickets, participants had more tickets from their 72-hour session to their RTP session and their asymptomatic session to their RTP session, but no differences were seen between their 72-hour session to their asymptomatic session. For stop sign tickets, participants had less tickets from their 72-hour session to their asymptomatic session and their 72-hour session to their RTP session, however no differences were seen between their asymptomatic session to their RTP session. For correct DA responses, participants performed more responses from their 72-hour session to their asymptomatic session and their 72-hour session to their RTP session, but no differences were seen between their asymptomatic session to their RTP session. For incorrect DA responses, participants had less responses from their 72-hour session to their asymptomatic session, however no differences were seen between their 72-hour session to their RTP session and their asymptomatic session to their RTP session. For missed DA responses, participants had less responses from their 72-hour session to their asymptomatic session and their 72-hour session to their RTP session, but no differences were seen between their asymptomatic session to their RTP session. For over the speed limit percentage, participants drove longer over the speed limit from their 72-hour session to their RTP session, however no differences were seen between their 72-hour session to their asymptomatic session and their asymptomatic session to their RTP session. For pedestrian collision response time, participants performed faster from their 72-hour session to their asymptomatic session and 72-hour session to their RTP session, but no differences were seen their asymptomatic session to their RTP session. Lastly, for car collision response time, participants performed faster from 72-hour session to their RTP session and their asymptomatic session to their RTP session, however no differences were seen between their 72-hour session to their asymptomatic session (Table 14).

Table 13. *Descriptives of Simulated Driving Performance in Car Following with DA Scenario*

	Concussed Athletes			Non-Concussed Athletes		
	Within 72 hours	Asymptomatic	RTP	Within 72 hours	Asymptomatic	RTP
DA Total Response Time						
M	1.9	1.4	1.2	1.9	1.5	1.2
(SD)	0.5	0.4	0.4	0.5	0.5	0.3
Car Collisions						
M	0.0	0.0	0.0	0.0	0.0	0.0
(SD)	0.0	0.0	0.0	0.0	0.0	0.0
Pedestrian Collisions						
M	0.1	0.1	0.1	0.0	0.0	0.0
(SD)	0.2	0.3	0.3	0.0	0.0	0.0
Speeding Tickets						
M	2.6	2.5	4.0	2.0	3.0	3.7
(SD)	3.2	2.9	4.3	2.5	3.5	3.5
Stop Sign Tickets						
M	1.8	1.2	0.8	1.1	0.8	0.4
(SD)	1.6	1.5	1.5	1.4	1.2	0.5

Table 13. *(cont'd)*

Road Edge Excursions						
M	0.0	0.0	0.0	0.1	0.0	0.0
(SD)	0.0	0.0	0.0	0.2	0.0	0.0
Correct DA Responses						
M	20.4	22.1	22.2	20.1	21.5	22.4
(SD)	2.3	1.1	1.6	2.7	1.8	1.0
Incorrect DA Responses						
M	0.2	0.0	0.0	0.1	0.0	0.1
(SD)	0.4	0.0	0.0	0.3	0.0	0.3
Missed DA Responses						
M	2.4	1.0	0.8	2.8	1.5	0.5
(SD)	2.2	1.1	1.6	2.7	1.8	0.8
Over Speed Limit Percentage						
M	5.0	4.2	7.0	2.4	7.2	6.5
(SD)	8.8	7.1	8.5	4.0	11.6	8.9
Pedestrian Collision Response Time						
M	2.4	1.5	1.5	2.7	1.9	1.3
(SD)	1.2	0.7	1.0	1.0	1.1	0.8
Car Collision Response Time						
M	1.9	1.6	0.9	1.9	1.7	1.5
(SD)	0.8	0.8	0.3	1.0	0.9	0.8

Table 14. *Descriptives of Simulated Driving Performance in Car Following with DA Scenario by Time (M ± SD)*

	All Participants *n=38*		
	Within 72 hours	Asymptomatic	RTP
DA Total Response Time	1.9±0.1	1.5±0.1	1.2±0.1
Car Collisions	0.0±0.0	0.0±0.0	0.0±0.0
Pedestrian Collisions	0.0±0.0	0.1±0.0	0.1±0.0
Speeding Tickets	2.3±0.5	2.7±0.5	3.8±0.6
Stop Sign Tickets	1.5±0.2	1.0±0.2	0.6±0.2
Road Edge Excursions	0.0±0.0	0.0±0.0	0.0±0.0
Correct DA Responses	20.3±0.4	21.8±0.2	22.3±0.2
Incorrect DA Responses	0.2±0.1	0.0±0.0	0.5±0.0
Missed DA Responses	2.6±0.4	1.2±0.2	0.7±0.2
Over Speed Limit Percentage	3.7±1.1	5.7±1.6	6.7±1.4
Pedestrian Collision Response Time	2.6±0.2	1.7±0.2	1.4±0.1
Car Collision Response Time	1.9±0.2	1.6±0.1	1.2±0.1

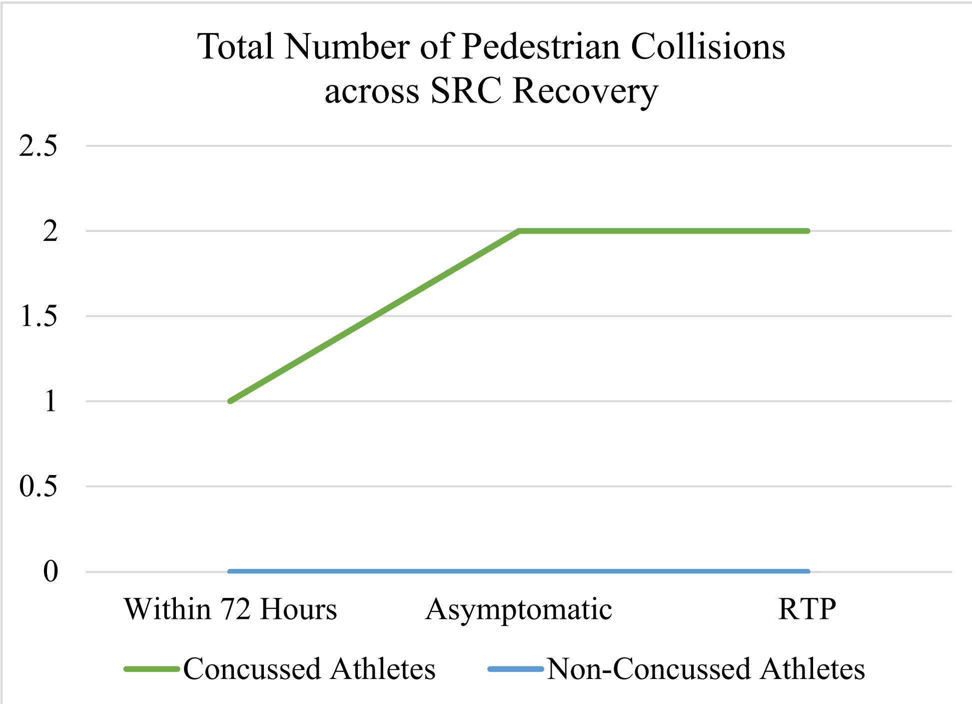

Figure 4. *Total Number of Pedestrian Collisions across Concussion Recovery*

Simulated Driving Performance in Concussed and Non-Concussed Athletes: Passing, Gap Judging and Merging Scenario

A 2 (group) X 3 (time) repeated measures MANOVA was performed to assess differences on simulated driving performance (i.e. road lane excursions, pedestrian collisions, car collisions, speeding tickets, turn signal usage, over speed limit percentage) between concussed and non-concussed high school and collegiate athletes, over the 3 previously described time points. There was no between group ($F_{1,31}$=1.34, p=0.27) main effect, time main effect ($F_{1,25}$=0.78, p=0.67), or group-by-time ($F_{1,25}$=0.81, p=0.64) interaction for simulated driving performance (Table 15). Even though group was non-significant, it is important to note that five concussed participants had six car collisions during this particular scenario, while non-concussed athletes had one car collision, over the critical indicators of SRC recovery. This was furthered examined in the between subjects' univariate and was found at p=0.02 (Figure 5).

Table 15. *Descriptives of Simulated Driving Performance in Passing, Gap Judging and Merging Scenario*

	Concussed Athletes			Non-Concussed Athletes		
	Within 72 hours	Asymptomatic	RTP	Within 72 hours	Asymptomatic	RTP
Turn Signal: Good Performance						
M	3.4	3.5	3.5	3.5	3.6	3.4
(SD)	0.6	0.8	0.6	0.7	0.8	0.5
Turn Signal: Poor Performance						
M	0.7	0.7	0.8	0.6	0.6	0.7
(SD)	0.9	0.7	0.6	0.6	0.5	0.5
Turn Signal: Missed Performance						
M	0.5	0.4	0.2	0.4	0.2	0.4
(SD)	0.7	0.8	0.4	0.5	0.5	0.6
Car Collisions						
M	0.2	0.1	0.1	0.0	0.0	0.1
(SD)	0.4	0.2	0.2	0.0	0.0	0.2
Pedestrian Collisions						
M	0.0	0.0	0.0	0.0	0.0	0.0
(SD)	0.0	0.0	0.0	0.0	0.0	0.0
Speeding Tickets						
M	1.8	1.1	1.5	1.6	1.3	1.6
(SD)	2.2	1.3	1.6	1.7	1.7	2.4
Road Edge Excursions						
M	0.0	0.0	0.0	0.0	0.0	0.0
(SD)	0.0	0.0	0.0	0.0	0.0	0.0

Table 15. *(cont'd)*

Over Speed Limit Percentage						
M	6.6	5.6	7.4	6.6	9.3	7.7
(SD)	9.8	9.9	10.1	9.8	15.6	11.7

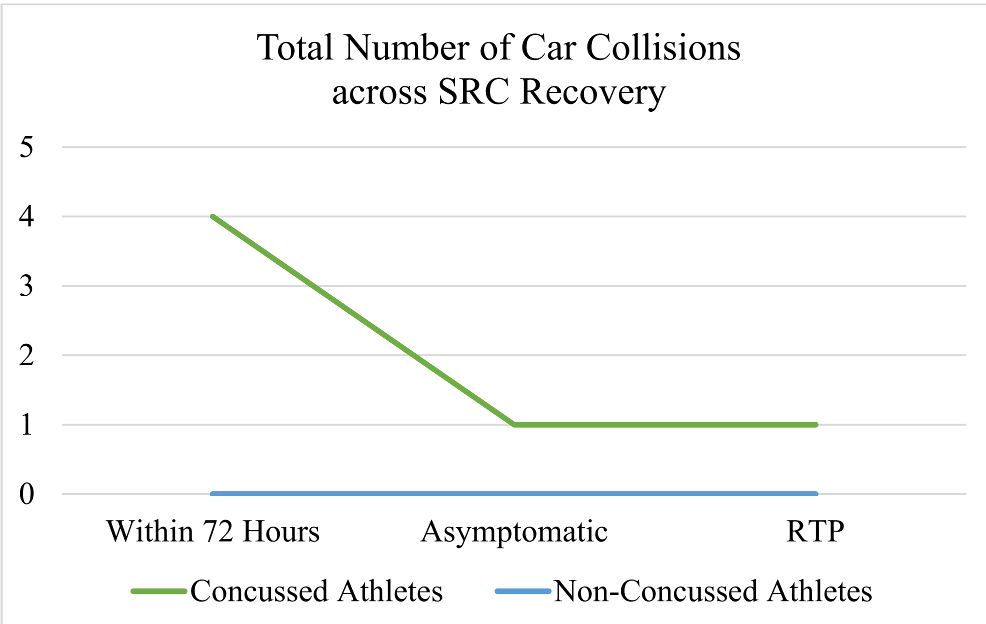

Figure 5. *Total Number of Pedestrian Collisions across Concussion Recovery*

4.3.3. The Relationship between Simulated Driving Performance and SRC Tools: Memory, Planning, and Navigation Scenario

All of the moderate to strong correlations for the three critical indicators of concussion recovery, of the concussed athletes, are presented in Tables 16-18. The current scenario observed numerous moderate and strong correlations (ρ=0.50 - 0.76) between SRC tools and simulated driving performance, during the critical indicators of the concussion recovery. Within the 72-hour session, the BESS test (ρ=0.50) and VOMS (ρ=-0.54 - 0.53) were found to have moderate correlations with simulated driving performance. Within the hard surface of the BESS, if a concussed athlete had more total number of errors, they had a better performance of turn signal usage. Within the VOMS, if a concussed athlete had more VMS domain symptoms, they committed lower turn signal usage. Furthermore, if a concussed athlete had more vertical saccades domain symptoms, they committed worse turn signal usage. Lastly, if a concussed athlete had more smooth pursuit domain symptoms, they drove over the speed limit longer (Table 16).

Table 16. *Moderate Correlations between SRC Tools and Simulated Driving Performance within the 72-Hour Session of the Concussion Recovery*

		Concussed Athletes *n=19*	
SRC Tools	Simulated Driving Performance	ρ	*p*
BESS:			
Hard Total Errors*	Turn Signal: Missed Performance*	-0.50	0.030
VOMS:			
VMS Domain*	Turn Signal: Good Performance	-0.54	0.016
Vertical Saccades Domain*	Turn Signal: Missed Performance*	0.53	0.020
Smooth Pursuit Domain*	Over Speed Limit Percentage*	0.50	0.030

*Indicates that a higher value represents poorer performance.

Within the asymptomatic session, the BESS test (ρ=-0.50 - 0.52) and ImPACT (ρ=-67 - 0.76) were found to have moderate to strong correlations with simulated driving performance. Within the soft surface of the BESS, if a concussed athlete had more total number of errors, they had lower turn signal usage. Furthermore, if a concussed athlete had more total number of errors on the hard surface of the BESS, they committed more road lane excursions. Within the ImPACT, if a concussed athlete had poorer performance on the verbal or visual memory composite scores, they committed worse turn signal usage. In addition, if a concussed athlete had a slower reaction time composite score, they committed better turn signal usage. Lastly, if a concussed athlete had poorer performance within the visual motor speed composite score, they committed worse turn signal usage (Table 17).

Table 17. *Moderate to Strong Correlations between SRC Tools and Simulated Driving Performance within the Asymptomatic Session of the Concussion Recovery*

		Concussed Athletes *n=19*	
SRC Tools	Simulated Driving Performance	ρ	*p*
BESS:			
Soft Total Errors*	Turn Signal: Good Performance	-0.50	0.031
	Turn Signal: Poor Performance*	0.52	0.022
Hard Total Errors*	Road Edge Excursions*	0.65	0.003
ImPACT:			
Verbal Memory Composite	Turn Signal: Missed Performance*	-0.55	0.015
Visual Memory Composite	Turn Signal: Missed Performance*	-0.65	0.003
Reaction Time* Composite	Turn Signal: Missed Performance*	-0.67	0.002
Visual Motor Speed Composite	Turn Signal: Poor Performance*	0.57	0.011
	Turn Signal: Missed Performance*	0.76	<0.001

*Indicates that a higher value represents poorer performance.

Within the RTP session, the ImPACT (ρ=-0.67-0.70) was found to have moderate to strong correlations with simulated driving performance. Within the ImPACT, if a concussed athlete had poorer performance within the visual memory composite score, they had a better performance of turn signal usage. Furthermore, if a concussed athlete had poorer performance within the visual motor speed composite score, they committed worse turn signal usage. Additionally, if a concussed athlete had a slower reaction time composite score, they committed worse turn signal usage. Lastly, if a concussed athlete had poorer performance within the impulse control composite score, they committed worse turn signal usage and had fewer speeding tickets (Table 18).

Table 18. *Moderate to Strong Correlations between SRC Tools and Simulated Driving Performance within the RTP Session of the Concussion Recovery*

SRC Tools	Simulated Driving Performance	Concussed Athletes *n=19* ρ	*p*
ImPACT:			
Visual Memory Composite	Turn Signal: Missed Performance*	0.62	0.005
Visual Motor Speed Composite	Turn Signal: Missed Performance*	-0.62	0.005
Reaction Time Composite*	Turn Signal: Missed Performance*	0.70	0.001
	Turn Signal: Poor Performance*	-0.67	0.002
Impulse Control Composite*	Turn Signal: Missed Performance*	0.56	0.013
	Speeding Tickets*	-0.51	0.025

*Indicates that a higher value represents poorer performance.

The Relationship between Simulated Driving Performance and SRC Tools: Car Following with DA Scenario

All of the moderate correlations for the three critical indicators of concussion recovery, of the concussed athletes, are presented in Tables 19-21. The current scenario observed numerous moderate to strong correlations (ρ=0.50-0.90) between SRC tools and simulated driving performance, during the critical indicators of the concussion recovery. Within the 72-hour session, the BESS test (ρ=-0.55) and ImPACT (ρ=-0.58) were found to have moderate correlations with simulated driving performance. Within the hard surface of the BESS, if a concussed athlete had more total number of errors, they had less stop sign tickets. Within the ImPACT, if a concussed athlete had poorer performance within their visual memory composite score, they had more stop sign tickets (Table 19).

Table 19. *Moderate Correlations between SRC Tools and Simulated Driving Performance within the 72-Hour Session of the Concussion Recovery*

		Concussed Athletes *n=19*	
SRC Tools	Simulated Driving Performance	ρ	*p*
BESS: Hard Total Errors*	Stop Sign Tickets*	-0.55	0.015
ImPACT: Visual Memory Composite	Stop Sign Tickets*	-0.58	0.009

*Indicates that a higher value represents poorer performance.

Within the asymptomatic session, symptoms (ρ=-0.57 - -0.59) and ImPACT (ρ=0.53) were found to have moderate correlations with simulated driving performance. Within symptoms, if a concussed athlete had a more total number of symptoms and severity, they had less stop sign tickets. Within the ImPACT, if a concussed athlete had poorer performance within their visual memory composite score, they had a slower total response time on the DA tasks within the current scenario. (Table 20).

Table 20. *Moderate Correlations between SRC Tools and Simulated Driving Performance within the Asymptomatic Session of the Concussion Recovery*

		Concussed Athletes *n=19*	
SRC Tools	Simulated Driving Performance	ρ	*p*
Symptoms:			
Total Number*	Stop Sign Tickets*	-0.59	0.008
Total Severity*	Stop Sign Tickets*	-0.57	0.011
ImPACT:			
Visual Memory Composite	DA Total Response Time*	-0.53	0.019

*Indicates that a higher value represents poorer performance.

Within the RTP session, the ImPACT (ρ=-0.75 - 0.63) and VOMS (ρ=-0.61 - 0.50) were found to have moderate to strong correlations with simulated driving performance. Within the VOMS, if a concussed athlete had more VMS domain symptoms, they committed less correct and missed DA responses, and were slower to react to pedestrian collisions. Within the ImPACT, if a concussed athlete had poorer performance within their visual motor speed composite score, they performed worse and slower on DA responses, had more speeding tickets, drove over the speed limit longer, and were slower to react to car collisions. Moreover, if a concussed athlete had poorer performance within their reaction time composite score, they performed worse and slower on DA responses, had more stop sign tickets, and drove over the speed limit longer (Table 21).

Table 21. *Moderate to Strong Correlations between SRC Tools and Simulated Driving Performance within the RTP Session of the Concussion Recovery*

SRC Tools	Simulated Driving Performance	Concussed Athletes *n=19* ρ	*p*
VOMS:			
VMS Domain*	Correct DA Responses	-0.61	0.006
	Missed DA Responses*	-0.61	0.006
	Pedestrian Collision Response Time*	0.50	0.030
ImPACT:			
Visual Motor Speed Composite	DA Total Response Time*	-0.56	0.012
	Speeding Tickets*	-0.64	0.003
	Correct DA Responses	0.50	0.029
	Missed DA Responses*	-0.50	0.029
	Over Speed Limit Percentage*	-0.75	<0.001
	Car Collision Response Time*	-0.61	0.006
Reaction Time* Composite	DA Total Response Time*	0.59	0.008
	Stop Sign Tickets*	0.63	0.004
	Correct DA Responses	-0.55	0.015
	Missed DA Responses*	0.55	0.015

Table 21. *(cont'd)*

	Over Speed Limit Percentage*	0.62	0.005
	Car Collision Response Time*	0.55	0.015

*Indicates that a higher value represents poorer performance.

The Relationship between Simulated Driving Performance and SRC Tools: Passing, Gap Judging and Merging Scenario

Within the 72-hour session, the ImPACT (ρ=0.51) was found to have a moderate correlation with simulated driving performance. Within ImPACT, if a concussed athlete had poorer performance within their reaction time composite, they had a better performance of signal usage. (Table 22).

Table 22. *Moderate Correlations between SRC Tools and Simulated Driving Performance within the 72-Hour Session of the Concussion Recovery*

		Concussed Athletes *n=19*	
SRC Tools	Simulated Driving Performance	ρ	*p*
ImPACT:			
Reaction Time* Composite	Turn Signal: Good Performance	0.51	0.025

*Indicates that a higher value represents poorer performance.

Within the asymptomatic session, the SRC tool (VOMS) was found to have a strong correlation (ρ=0.73) with simulated driving performance. Within VOMS, if a concussed athlete had more smooth pursuit domain symptoms, they committed more car collisions. (Table 23).

Table 23. *Moderate to Strong Correlations between SRC Tools and Simulated Driving Performance within the Asymptomatic Session of the Concussion Recovery*

SRC Tools	Simulated Driving Performance	Concussed Athletes *n=19* ρ	*p*
VOMS: Smooth Pursuit Domain*	Car Collisions*	0.73	<0.001

*Indicates that a higher value represents poorer performance.

Within the RTP session, the BESS (ρ=0.58), VOMS (ρ=0.50), and ImPACT (ρ=-0.64 - -0.54) were found to have moderate correlations with simulated driving performance. Within the soft surface of the BESS, if an athlete had more total number of errors, they had worse turn signal usage. Within VOMS, if a concussed athlete had more VMS domain symptoms, they had better turn signal usage. Within ImPACT, if a concussed athlete had poorer performance within their visual motor speed composite score, they had more speeding tickets. Within ImPACT, if an athlete had poorer performance within their impulse control composite score, they had better turn signal usage (Table 24).

Table 24. *Moderate Correlations between SRC Tools and Simulated Driving Performance within the RTP Session of the Concussion Recovery*

SRC Tools	Simulated Driving Performance	Concussed Athletes *n=19* ρ	*p*
BESS: Soft Total Errors*	Turn Signal: Poor Performance*	0.58	0.009
VOMS: VMS Domain*	Turn Signal: Good Performance	0.50	0.031
ImPACT: Visual Motor Speed Composite	Speeding Tickets *	-0.54	0.017

Table 24. *(cont'd)*

Impulse Control Composite*	Turn Signal: Missed Performance*	-0.64	0.003

*Indicates that a higher value represents poorer performance.

CHAPTER 5

DISCUSSION

5.1. Overview of Study

The purpose of this study was to examine the test-retest reliability of the STISIM Drive® software and the simulator among collegiate students, with one week in between test sessions. Results from the test-retest, revealed a range of poor to good reliability of the driving scenarios, among collegiate students. Moderate to good ICC values were found in good, poor, and missed turn signal usage, speeding and stop sign tickets, centerline crossings, DA total response time and road edge excursions. Even though no significant statistical differences were found for group or the interaction of group and time, concussed athletes presented with worse clinical outcomes, such as the pedestrian and car collisions, compared to their counterparts. This study also observed several correlations between simulated driving performance and SRC tools (i.e. symptoms, balance, neurocognition, VOMS) among the concussed group. These preliminary findings may guide healthcare providers, educators, and researchers in developing a comprehensive driving evaluation for concussed individuals.

Test-Retest Reliability of the STISIM Drive® Software

Evaluating changes or deficits in driving performance should be considered as part of the healthcare provider's SRC management practice. The STISIM Drive® software is designed for medical and occupational therapy applications and is used to facilitate the diagnosis, evaluation, treatment, and rehabilitation process of the needs of patients experiencing a head injury or impairment. A key advantage of the STISIM Drive® software, is the ease of delivery, meaning it allows healthcare providers to create and utilize pre-designed scenarios to track the evaluation process, interpret the driving results, and plan a treatment for each patient. Driving simulations appear to be a sensitive method to evaluate driving performance[240-242] and the STISIM Drive® software has been shown to correlate with on-road testing.[223,227] However, additional research is needed to examine the test-retest reliability of the STISIM Drive® software and simulators.

The current study strongly supported the memory, planning, and navigation scenario for acceptable reliability, however the study partially supported the car following with DA scenario and the passing, gap judging and merging scenarios, due to poor to moderate reliability. Within the memory, planning, and navigation scenario, turn signal usage, road edge excursions, centerline crossings, and speeding tickets were found to have moderate to good reliability, while over the speed limit percentage was approaching moderate reliability. Importantly, no participants collided with other vehicles during the current scenario. Within the car following with DA scenario, stop sign tickets and DA total response times were found to have moderate reliability. However, speeding tickets, DA responses, and over the speed limit percentage had poor reliability. Additionally, no participants collided with other vehicles or pedestrians, and had no road lane excursions during this particular scenario. Within the passing, gap judging and merging scenario, turn signal usage, speeding tickets, and over the speed limit percentage reflected poor reliability. Furthermore, no participants collided with other vehicles or pedestrians, and had no road lane excursions during this present scenario.

While the study found moderate to good reliability among several driving measures across the scenarios, some driving measures were found to have poor reliability (i.e. speeding tickets, driving longer over the speed limit, and DA responses). A possible explanation for poor reliability on speeding tickets and over the speed limit percentage, could be due to the participant not adjusting to the spring-loaded gas and brake pedals within the simulator, as compared to a vehicle with hydraulic pedals. For the poor reliability on correct, incorrect and missed DA responses, participants could have had trouble locating the buttons on the steering wheel to insinuate a DA task response was activated within the scenario. These DA response buttons are not normally located on a steering wheel in an actual vehicle, which could have led to poor learning effects of these buttons within the simulator. Lastly, turn signal usage could have also be a concern within the simulator, since the turn signals controls were paddles instead of levers within an actual vehicle. Future studies should examine the use of hydraulic pedals and turn signal levers, to mimic a vehicle more accurately, than the equipment used in the current study.

Notably, the current study found that road edge excursions, car and pedestrian collisions were good predictors of the STISIM Drive® software, due to no one colliding with another pedestrian or vehicle and committed no road lane excursions at any point within any given scenario. This indicates that participants could drive within their lane, without driving over the right line of the road into the sidewalk. When examining pedestrian collisions within the driving scenarios, participants were able to navigate around pedestrians crossing in the crosswalk and pedestrians unexpectedly walking in front of the on-coming moving vehicle. Lastly regarding car collisions, participants were able to navigate around traffic and taking left turns in front of on-coming traffic, as well as vehicles unexpectedly pulling out in front of the on-coming moving vehicle. These driving measures of the STISIM Drive® software could be due to the force feedback steering wheel of the simulator, which could have been a good indicator that participants felt comfortable with the steering wheel, which mimicked the feel of a realistic car.

Simulated Driving Performance in Concussed and Non-Concussed Athletes

It is well-established that driving performance depends on an individual’s ability to multi-task in several different domains, such as cognitive, visual, and motor function abilities. Accordingly, an impairment in cognitive functioning is a predictor of worse driving outcomes.[28,243] Much of the research in this area has been conducted in individuals with severe cognitive conditions (i.e. TBI, Alzheimer's disease), however little research has examined the role that SRC plays in driving ability. The question remains for healthcare professionals working with concussed athletes, is how long do the impairments of a SRC last and how do we decide when it is safe for our athletes to return to drive? A 2016 article[215] reported that at 8 different locations of a Nationwide Children's hospital, approximately 9% of their sports medicine staff documented driving recommendations for their concussed patients. Even though there are various reasons of the low rate of providing driving recommendations, there are no clear guidelines or consensus statements regarding the timing of returning a concussed athlete back to driving. Furthermore, driving recommendations have largely been based on clinical experience and expert opinion.

In the current study, athletes who sustained a SRC who were asymptomatic and cleared for full return to sport participation presented with more car and pedestrian collisions, as compared with non-concussed matched controls. Moreover, four concussed athletes (21.1%) had five pedestrian collisions and five concussed athletes (26.3%) had 6 car collisions in the driving scenarios, resulting in a total of 11 collisions from nine concussed athletes (47.4%). Even though there were no significant differences between group or group X time, this notorious finding in concussed athletes is clinically meaningful! Additionally, concussed athletes continued to collide with pedestrians and other vehicles throughout the SRC recovery period. This finding is in contrast to Schmidt et al.[41], who found no differences in total crashes among concussed and non-concussed participants. With concussed athletes colliding with more pedestrians and other vehicles, this could lead to an increase in financial burden to both potential parties among vehicle damages and medical bills for injuries, legal actions, and funeral arrangements for a possible death of someone in the accident. Furthermore, this could also lead to a decrease in social aspects of life, which could cause mental conditions (i.e. depression), family or care-taker burden, and/or isolation and lack of independence.

There is limited evidence to suggest that clinicians should consider recommending driving restrictions for the first 24-hours[28,212,213] up to the asymptomatic stage[41] of a sustained mTBI. Within the first 24-hours of a sustained mTBI, Preece et al.[28,213] found mTBI patients were significantly slower to react to traffic hazards on the UQ-HPT, when compared to the minor orthopedic injuries group, while Baker et al.[212] found slower times on the OT-DHMT in mTBI patients. In another study conducted by Preece et al.[28], they found that mTBI patients detected fewer traffic hazards, when compared to the controls. These findings from mTBI patients are similar to the current study, as athletes were colliding with other vehicles and pedestrians and were slower to react to these hazards. Further investigation is necessary to determine the specific time-point at which concussed individuals should return to driving.

This was the first study to examine other driving variables that have not been examined in other studies, which included DA total response time, DA responses, turn signal usage, and over the speed limit percentage. However, no differences were seen in these particular variables between concussed and non-concussed athletes. However, when examining the asymptomatic stage of a sustained concussion, Schmidt et al.[41] found more right lane excursions compared to a control group, however this study found no differences in right lane excursions on any of the three driving scenarios, at any critical indicators of the SRC recovery. A possible reason as to why this study did not see any road lane excursions in any driving scenarios, at any time session, could be due to the force feedback steering wheel that was utilized in our simulator, to mimic the feel of a steering wheel in an actual vehicle. Additionally, Schmidt et al.[41] only used a simulated wheel and pedal system through a desktop computer, compared to the study's custom-built simulator. However, similar findings were found when compared to Schmidt et al.[41], as no differences were seen with speeding or stop sign tickets among concussed and non-concussed participants. This could be due to the realistic nature of abiding by the law in regard to speeding or stopping at a stop sign. Another possible explanation is that the participants knew that the research investigator was watching their driving performance throughout their testing and could have felt tenser while driving, in order to perform better and have less tickets.

The Relationship between Simulated Driving Performance and SRC Tools

Further evidence concerning methods used to determine fitness to drive following a SRC is needed among concussed athletes. This study provides preliminary direction regarding common SRC tools, that may best indicate continued driving impairment following a SRC. During the current study, there were several moderate-strong relationships between SRC tools and driving measures, throughout the critical indicators of the SRC recovery, among the concussed athletes. More specifically, ImPACT had the strongest relationships, followed by BESS and VOMS for the SRC tools, which were associated worse turn signal usage, DA responses, and stop sign tickets. These results provide a starting point to guide further research ultimately aimed at providing clinicians tools to guide driving recommendations based on neuropsychological performance, since simulators are not easily accessible in the clinical setting.

In the current study, there were four SRC measures that strongly correlated with simulated driving performance. Within the asymptomatic session of a sustained SRC, the study found that if concussed athletes had poorer visual motor speed on the ImPACT, that they would have worse or even no turn signal usage. This could be due to the inability to efficiently integrate the driver's eyes and their visual field while driving, and simultaneously using their hands to complete the task of turning on their turn signal. Additionally, the study found that if concussed athletes had higher symptoms on their VOMS smooth pursuit domain, it was correlated with more car collisions. This relationship could be due to having higher severity of symptoms and the saccades nature of the smooth pursuit domain, the concussed athletes may have less ability to react to a slow-moving vehicle pulling out in front of them unexpectedly or turning against on-coming traffic. Lastly within the RTP testing session, concussed athletes presented with slower reaction times on the ImPACT, which correlated with poorer turn signal usage. The study also found poorer performance on visual motor speed on the ImPACT, which correlated with driving over the speed limit longer, during the RTP testing session. A possible reason of slower reaction times could be due to when concussed athletes are turning or changing lanes, it takes them longer to put on their turn signal and could result in worse consequences to them and/or others on the road by not showing their intentions. Additionally, it could cause the inability to efficiently integrate the driver's eyes and their visual field while driving, and simultaneously using their foot to use the gas pedal and to stay under the speed limit. Even though turn signal usage and driving over the speed limit longer may not be high-risk driving measures, such as a pedestrian or vehicle collision, turn signals allow other drivers on the road to know your intentions of turning or changing lanes. If one did not use their turn signals, it could lead to unintentional accidents between the concussed driver and others on the road. Furthermore, driving over the speed limit longer is considered risky driving and therefore could have fatal costs on all parties involved, such as greater potential for loss of vehicle control, increased degree of crash severity leading to more severe injuries and increased stopping distance after the driver perceives danger.

A small cohort study[41] conducted testing within 48 hours after symptom resolution in concussed athletes and students and explored the relationship between several neuropsychological assessments and driving performance. Even though they used different neuropsychological tests than the current study, they found several strong and significant correlations between symbol digit modalities, Rey Osterrieth Complex Figure accuracy, and the CNS Vital Signs verbal memory and motor speed domains with more road lane excursions, total crashes and more total tickets. These findings along with the current study provide some direction regarding which neuropsychological functions and SRC tools may predict driving performance. In addition, these findings are also supported by a few different researchers, who found evidence that verbal and visual memory, attention, processing speed, and cognitive flexibility can predict the ability to return to drive after sustaining a TBI.[244,245] However, the generalizability of these findings to the population of athletes with SRCs is still left unclear.

5.2. Limitations

The current study had several limitations. The first limitation is in regard to the participants. We had a small sample size for concussed and non-concussed athletes, as well as the participants were recruited from the Mid-Michigan area, which cannot be generalizable to the entire US high school and collegiate populations. Secondly, there were unequal groups for sex (i.e. male, female) and level of sport (i.e. high school, club, collegiate). Even though these factors were not discussed and focused on in the current study, one could not make assumptions for these populations in their simulated driving ability. Another limitation of the study was that even though simulated driving has been validated as a reliable measure of evaluating driving abilities, on-road driving performance may produce different effects. Lastly, the simulation of the road environment was not as “realistic” as on-road driving. This topic is very complicated, because the more details that are provided in the scenario, the slower the simulator will run.

5.3. Conclusion

Based upon these differences in driving performance between concussed and non-concussed athletes, future studies are needed to continue to investigate simulated driving performance among concussed athletes in order to create recommendations and guidelines for clinicians. Additionally, we need to continue to investigate what SRC tools comprise the best evaluation of return to drive in athletic populations. Furthermore, additional longitudinal studies are needed to track simulated driving performance further out from the return to full participation stage, since concussed athletes are sustaining more pedestrian and car collisions than non-concussed athletes. The decision regarding return to drive after a SRC is a very difficult decision, with limited research to make guidelines and recommendations for clinicians. Even though this study shows merit, it could be reasonable to develop supportive strategies which encourage concussed patients to reduce their speed, avoid night-time driving, avoid driving while fatigued, limit distractions (i.e. radio, people in the vehicle, cell phone use), and low traffic time. This may reduce the temporary safety risk, while they return back to baseline for their return to school and return to sport participation.

APPENDICES

APPENDIX A: Demographic Survey: SRC Injury Group

Subject Identification: ______________________________

1. **Date: __________/__________/__________**

2. **Date of Birth: __________/__________/__________**

3. **Age: __________________**

4. **Gender (Check one):** ☐ Male ☐ Female

5. **Race (Check one):**
   ☐ Asian
   ☐ Native American or Alaska Native
   ☐ Native Hawaiian or Other Pacific Islander
   ☐ Hispanic Black
   ☐ Non-Hispanic Black or African American
   ☐ Hispanic White
   ☐ Non-Hispanic White
   ☐ Other ________________________________

6. **Height: __________/__________**
   Feet **Inches**

7. **Weight: ____________________** Pounds

8. **Handedness (Check one):** ☐ Right ☐ Left ☐ Both

9. Sport (Check one):

- ☐ Football
- ☐ Soccer
- ☐ Field Hockey
- ☐ Ice Hockey
- ☐ Basketball
- ☐ Lacrosse
- ☐ Swimming/Diving
- ☐ Golf
- ☐ Volleyball
- ☐ Tennis
- ☐ Rowing
- ☐ Baseball
- ☐ Softball
- ☐ Cheerleading
- ☐ Cross Country
- ☐ Track/Field
- ☐ Wrestling
- ☐ Other ________________________________

10. Academic Year (Check one):

- ☐ Freshman
- ☐ Sophomore
- ☐ Junior
- ☐ Senior
- ☐ Other _______________________

11. Contacts/Glasses (Check one): ☐ Yes ☐ No

If yes, are they wearing them now (Check one)? ☐ Yes ☐ No

12. Current GPA (Based on 4.0 scale): _____._____

13. Concussion History:

Have you ever had a previous concussion: ☐ Yes ☐ No ☐ Unknown

Date of previous concussion not including current: ________________

If yes, how many previous concussion(s) have you had? ______________________

14. Date of Injury: __________/__________/__________

15. Time of Injury: _______:_______

16. Situation:
☐ NCAA practice
☐ NCAA game
☐ Club practice
☐ Club game

17. Play:
☐ Offensive
☐ Defensive

18. Mechanism of Injury (Select all that apply):
☐ Tackled by opponent
☐ Tackled an opponent
☐ Blocking
☐ Contact with ground
☐ Contact with barrier/object/ball
☐ Collision with opponent
☐ Collision with teammate
☐ Checking an opponent
☐ Checked by an opponent
☐ Other ____________________________________

APPENDIX B: Demographic Survey: Match Control Group

Subject Identification: ______________________________

1. **Date: __________/__________/__________**

2. **Date of Birth: __________/__________/__________**

3. **Age: __________________**

4. **Gender (Check one):** ☐ Male ☐ Female

5. **Race (Check one):**
   - ☐ Asian
   - ☐ Native American or Alaska Native
   - ☐ Native Hawaiian or Other Pacific Islander
   - ☐ Hispanic Black
   - ☐ Non-Hispanic Black or African American
   - ☐ Hispanic White
   - ☐ Non-Hispanic White
   - ☐ Other ________________________________

6. **Height: __________/__________**
   Feet Inches

7. **Weight: ____________________** Pounds

8. **Handedness (Check one):** ☐ Right ☐ Left ☐ Both

9. Sport (Check one):

- ☐ Football
- ☐ Soccer
- ☐ Field Hockey
- ☐ Ice Hockey
- ☐ Basketball
- ☐ Lacrosse
- ☐ Swimming/Diving
- ☐ Golf
- ☐ Volleyball
- ☐ Tennis
- ☐ Rowing
- ☐ Baseball
- ☐ Softball
- ☐ Cheerleading
- ☐ Cross Country
- ☐ Track/Field
- ☐ Wrestling
- ☐ Other ________________________________

10. Academic Year (Check one):

- ☐ Freshman
- ☐ Sophomore
- ☐ Junior
- ☐ Senior
- ☐ Other _______________________

11. Contacts/Glasses (Check one): ☐ Yes ☐ No

If yes, are they wearing them now (Check one)? ☐ Yes ☐ No

12. Current GPA (Based on 4.0 scale): _____._____

13. Matched Control Subject: Linked to Injury Subject: 1 - ___ ___

14. Concussion History:

Have you ever had a previous concussion (Check one): ☐ Yes ☐ No ☐ Unknown

Date of last concussion: ____________________________

If yes, how many previous concussion(s) have you had? ______________________

APPENDIX C: Demographic Survey: Test-Retest

Basic Demographics (Test-Retest)

Subject Identification: ______________________________

1. **Date:** __________/__________/__________

2. **Date of Birth:** __________/__________/__________

3. **Age:** __________________

4. **Gender (Check one):** ☐ Male ☐ Female

5. **Race (Check one):**
   - ☐ Asian
   - ☐ Native American or Alaska Native
   - ☐ Native Hawaiian or Other Pacific Islander
   - ☐ Hispanic Black
   - ☐ Non-Hispanic Black or African American
   - ☐ Hispanic White
   - ☐ Non-Hispanic White
   - ☐ Other ________________________________

6. **Height:** __________/__________
   Feet **Inches**

7. **Weight:** ____________________ Pounds

8. **Handedness (Check one):** ☐ Right ☐ Left ☐ Both

9. Academic Year (Check one):

□ Freshman
□ Sophomore
□ Junior
□ Senior
□ Other ________________________

10. Contacts/Glasses (Check one): □ Yes □ No

If yes, are they wearing them now (Check one)? □ Yes □ No

11. Current GPA (Based on 4.0 scale): _____._____

12. Concussion History:

Have you ever had a previous concussion (Check one): □ Yes □ No □ Unknown

Date of last concussion: _____________________________

If yes, how many previous concussion(s) have you had? _______________________

APPENDIX D: Driving Questionnaire

Subject Identification: ______________________________

1. What type of vehicle do you currently drive?
   - ☐ Sedan
   - ☐ SUV
   - ☐ Pickup
   - ☐ Coupe
   - ☐ Minivan
   - ☐ Wagon
   - ☐ Hatchback
   - ☐ Convertible
   - ☐ Full-Sized Van
   - ☐ Semi Truck
   - ☐ Other ______________________________

2. How many years have you been driving? ___________________________________

3. How many days of the week do you drive (1-7 days)? _________________________

4. How many hours do you typically drive in a week? ___________________________

5. Where do you typically drive?
   - ☐ Rural (Country)
   - ☐ Suburban (Residential area on the outskirts of a city)
   - ☐ Urban (City)
   - ☐ Other ______________________________

6. What is the average speed that you drive on the main roads (40mph)? _____mph

7. What is the average speed that you drive on the freeways (70mph)? _____mph

8. Do you use your cell phone to make or take phone calls while driving? ☐ Yes ☐ No

   a. If yes, how many minutes do you spend on your phone calls? _______minutes

   b. Do you notice if you tend to drive slower or faster than usual while talking on your phone? ☐ Slower ☐ Faster ☐ Same

9. Do you wear a headset or use Bluetooth when using your cell phone?
   □ Yes □ No

10. Do you use your cell phone to text while driving? □ Yes □ No

    a. If yes, how many texts do you send while driving on a typical day?
       ____

    b. If yes, how many texts do you read while driving on a typical day?
       ____

    c. Do you notice if you tend to drive slower or faster than usual while texting on your phone? □ Slower □ Faster □ Same

11. How many tickets have you received from an officer within the past 3 years?
    ____

12. How many times have you been pulled over by an officer regardless if you received a ticket or not, within the past 3 years? ______________________

13. How many accidents have you been in within the past 3 years? ___________________
    a. Who was at fault? □ You □ The other driver
    b. Explain the situation
       ____
       ____
       ____
       ____
       ____
       ____
       ____
       ____

14. Have you received a DUI within the past 3 years? □ Yes □ No

15. How often do you use you blinker/turn signal?
    □ Always
    □ Almost always
    □ Sometimes
    □ Seldom
    □ Never

16. What is your license type? ________________________________
(e.g. Type A-D, Class A-C)

17. Have you previously had an advanced driving training course within the past 3 years?
☐ Yes ☐ No

18. Do you consider yourself to be an aggressive driver? ☐ Yes ☐ No ☐ Sometimes

19. Do you wear a seatbelt? ☐ Yes ☐ No ☐ Sometimes

20. How fast do you drive compared to the average flow of traffic?
☐ Much faster
☐ Somewhat faster
☐ About the same
☐ Somewhat slower
☐ Much slower

21. How do you rate the quality of your driving?
☐ Excellent
☐ Good
☐ Average
☐ Fair
☐ Poor

22. Do you typically drive alone? ☐ Yes ☐ No ☐ Sometimes

1

IMMEDIATE OR ON-FIELD ASSESSMENT

The following elements should be assessed for all athletes who are suspected of having a concussion prior to proceeding to the neurocognitive assessment and ideally should be done on-field after the first first aid / emergency care priorities are completed.

If any of the "Red Flags" or observable signs are noted after a direct or indirect blow to the head, the athlete should be immediately and safely removed from participation and evaluated by a physician or licensed healthcare professional.

Consideration of transportation to a medical facility should be at the discretion of the physician or licensed healthcare professional.

The GCS is important as a standard measure for all patients and can be done serially if necessary in the event of deterioration in conscious state. The Maddocks questions and cervical spine exam are critical steps of the immediate assessment; however, these do not need to be done serially.

STEP 1: RED FLAGS

RED FLAGS:

- **Neck pain or tenderness**
- **Double vision**
- **Weakness or tingling/ burning in arms or legs**
- **Severe or increasing headache**
- **Seizure or convulsion**
- **Loss of consciousness**
- **Deteriorating conscious state**
- **Vomiting**
- **Increasingly restless, agitated or combative**

STEP 2: OBSERVABLE SIGNS

Witnessed ☐ Observed on Video ☐

Lying motionless on the playing surface	Y	N
Balance / gait difficulties / motor incoordination: stumbling, slow / laboured movements	Y	N
Disorientation or confusion, or an inability to respond appropriately to questions	Y	N
Blank or vacant look	Y	N
Facial injury after head trauma	Y	N

STEP 3: MEMORY ASSESSMENT MADDOCKS QUESTIONS[2]

"I am going to ask you a few questions, please listen carefully and give your best effort. First, tell me what happened?"

Mark Y for correct answer / N for incorrect

What venue are we at today?	Y	N
Which half is it now?	Y	N
Who scored last in this match?	Y	N
What team did you play last week / game?	Y	N
Did your team win the last game?	Y	N

Note: Appropriate sport-specific questions may be substituted.

Name: ____________________

DOB: ____________________

Address: ____________________

ID number: ____________________

Examiner: ____________________

Date: ____________________

STEP 4: EXAMINATION GLASGOW COMA SCALE (GCS)[3]

Time of assessment			
Date of assessment			
Best eye response (E)			
No eye opening	1	1	1
Eye opening in response to pain	2	2	2
Eye opening to speech	3	3	3
Eyes opening spontaneously	4	4	4
Best verbal response (V)			
No verbal response	1	1	1
Incomprehensible sounds	2	2	2
Inappropriate words	3	3	3
Confused	4	4	4
Oriented	5	5	5
Best motor response (M)			
No motor response	1	1	1
Extension to pain	2	2	2
Abnormal flexion to pain	3	3	3
Flexion / Withdrawal to pain	4	4	4
Localizes to pain	5	5	5
Obeys commands	6	6	6
Glasgow Coma score (E + V + M)			

CERVICAL SPINE ASSESSMENT

Does the athlete report that their neck is pain free at rest?	Y	N
If there is NO neck pain at rest, does the athlete have a full range of ACTIVE pain free movement?	Y	N
Is the limb strength and sensation normal?	Y	N

In a patient who is not lucid or fully conscious, a cervical spine injury should be assumed until proven otherwise.

OFFICE OR OFF-FIELD ASSESSMENT

Please note that the neurocognitive assessment should be done in a distraction-free environment with the athlete in a resting state.

STEP 1: ATHLETE BACKGROUND

Sport / team / school: ____________________

Date / time of injury: ____________________

Years of education completed: ____________________

Age: ____________________

Gender: M / F / Other

Dominant hand: left / neither / right

How many diagnosed concussions has the athlete had in the past?: ____________________

When was the most recent concussion?: ____________________

How long was the recovery (time to being cleared to play) from the most recent concussion?: ____________ (days)

Has the athlete ever been:

Hospitalized for a head injury?	Yes	No
Diagnosed / treated for headache disorder or migraines?	Yes	No
Diagnosed with a learning disability / dyslexia?	Yes	No
Diagnosed with ADD / ADHD?	Yes	No
Diagnosed with depression, anxiety or other psychiatric disorder?	Yes	No

Current medications? If yes, please list:

____

____

____

____

____

____

Name: ____________________

DOB: ____________________

Address: ____________________

ID number: ____________________

Examiner: ____________________

Date: ____________________

2

STEP 2: SYMPTOM EVALUATION

The athlete should be given the symptom form and asked to read this instruction paragraph out loud then complete the symptom scale. For the baseline assessment, the athlete should rate his/her symptoms based on how he/she typically feels and for the post injury assessment the athlete should rate their symptoms at this point in time.

Please Check: ☐ Baseline ☐ Post-Injury

Please hand the form to the athlete

	none	mild		moderate		severe	
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck Pain	0	1	2	3	4	5	6
Nausea or vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
Feeling like "in a fog"	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Difficulty concentrating	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	5	6
Fatigue or low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous or Anxious	0	1	2	3	4	5	6
Trouble falling asleep (if applicable)	0	1	2	3	4	5	6

Total number of symptoms:	of 22
Symptom severity score:	of 132
Do your symptoms get worse with physical activity?	Y N
Do your symptoms get worse with mental activity?	Y N
If 100% is feeling perfectly normal, what percent of normal do you feel?	

If not 100%, why?

____

____

____

Please hand form back to examiner

3

STEP 3: COGNITIVE SCREENING

Standardised Assessment of Concussion (SAC)[4]

Name: ______

DOB: ______

Address: ______

ID number: ______

Examiner: ______

Date: ______

ORIENTATION

What month is it?	0	1
What is the date today?	0	1
What is the day of the week?	0	1
What year is it?	0	1
What time is it right now? (within 1 hour)	0	1
Orientation score		of 5

IMMEDIATE MEMORY

The Immediate Memory component can be completed using the traditional 5-word per trial list or optionally using 10-words per trial to minimise any ceiling effect. All 3 trials must be administered irrespective of the number correct on the first trial. Administer at the rate of one word per second.

Please choose EITHER the 5 or 10 word list groups and circle the specific word list chosen for this test.

I am going to test your memory. I will read you a list of words and when I am done, repeat back as many words as you can remember, in any order. For Trials 2 & 3: I am going to repeat the same list again. Repeat back as many words as you can remember in any order, even if you said the word before.

List	Alternate 5 word lists					Score (of 5) Trial 1	Trial 2	Trial 3
A	Finger	Penny	Blanket	Lemon	Insect			
B	Candle	Paper	Sugar	Sandwich	Wagon			
C	Baby	Monkey	Perfume	Sunset	Iron			
D	Elbow	Apple	Carpet	Saddle	Bubble			
E	Jacket	Arrow	Pepper	Cotton	Movie			
F	Dollar	Honey	Mirror	Saddle	Anchor			
					Immediate Memory Score	of 15		
					Time that last trial was completed			

List	Alternate 10 word lists					Score (of 10) Trial 1	Trial 2	Trial 3
G	Finger	Penny	Blanket	Lemon	Insect			
	Candle	Paper	Sugar	Sandwich	Wagon			
H	Baby	Monkey	Perfume	Sunset	Iron			
	Elbow	Apple	Carpet	Saddle	Bubble			
I	Jacket	Arrow	Pepper	Cotton	Movie			
	Dollar	Honey	Mirror	Saddle	Anchor			
					Immediate Memory Score	of 30		
					Time that last trial was completed			

CONCENTRATION

DIGITS BACKWARDS

Please circle the Digit list chosen (A, B, C, D, E, F). Administer at the rate of one digit per second reading DOWN the selected column.

I am going to read a string of numbers and when I am done, you repeat them back to me in reverse order of how I read them to you. For example, if I say 7-1-9, you would say 9-1-7.

Concentration Number Lists (circle one)					
List A	List B	List C			
4-9-3	5-2-6	1-4-2	Y	N	0
6-2-9	4-1-5	6-5-8	Y	N	1
3-8-1-4	1-7-9-5	6-8-3-1	Y	N	0
3-2-7-9	4-9-6-8	3-4-8-1	Y	N	1
6-2-9-7-1	4-8-5-2-7	4-9-1-5-3	Y	N	0
1-5-2-8-6	6-1-8-4-3	6-8-2-5-1	Y	N	1
7-1-8-4-6-2	8-3-1-9-6-4	3-7-6-5-1-9	Y	N	0
5-3-9-1-4-8	7-2-4-8-5-6	9-2-6-5-1-4	Y	N	1
List D	List E	List F			
7-8-2	3-8-2	2-7-1	Y	N	0
9-2-6	5-1-8	4-7-9	Y	N	1
4-1-8-3	2-7-9-3	1-6-8-3	Y	N	0
9-7-2-3	2-1-6-9	3-9-2-4	Y	N	1
1-7-9-2-6	4-1-8-6-9	2-4-7-5-8	Y	N	0
4-1-7-5-2	9-4-1-7-5	8-3-9-6-4	Y	N	1
2-6-4-8-1-7	6-9-7-3-8-2	5-8-6-2-4-9	Y	N	0
8-4-1-9-3-5	4-2-7-9-3-8	3-1-7-8-2-6	Y	N	1
		Digits Score:			of 4

MONTHS IN REVERSE ORDER

Now tell me the months of the year in reverse order. Start with the last month and go backward. So you'll say December, November. Go ahead.

Dec - Nov - Oct - Sept - Aug - Jul - Jun - May - Apr - Mar - Feb - Jan	0 1
Months Score	of 1
Concentration Total Score (Digits + Months)	of 5

4

STEP 4: NEUROLOGICAL SCREEN

See the instruction sheet (page 7) for details of test administration and scoring of the tests.

Can the patient read aloud (e.g. symptom check-list) and follow instructions without difficulty?	Y	N
Does the patient have a full range of pain-free PASSIVE cervical spine movement?	Y	N
Without moving their head or neck, can the patient look side-to-side and up-and-down without double vision?	Y	N
Can the patient perform the finger nose coordination test normally?	Y	N
Can the patient perform tandem gait normally?	Y	N

BALANCE EXAMINATION

Modified Balance Error Scoring System (mBESS) testing[5]

Which foot was tested (i.e. which is the non-dominant foot) ☐ Left ☐ Right

Testing surface (hard floor, field, etc.) ____________

Footwear (shoes, barefoot, braces, tape, etc.) ____________

Condition	Errors
Double leg stance	of 10
Single leg stance (non-dominant foot)	of 10
Tandem stance (non-dominant foot at the back)	of 10
Total Errors	of 30

Name: ____________

DOB: ____________

Address: ____________

ID number: ____________

Examiner: ____________

Date: ____________

5

STEP 5: DELAYED RECALL:

The delayed recall should be performed after 5 minutes have elapsed since the end of the Immediate Recall section. Score 1 pt. for each correct response.

Do you remember that list of words I read a few times earlier? Tell me as many words from the list as you can remember in any order.

Time Started ____

Please record each word correctly recalled. Total score equals number of words recalled.

____

____

____

Total number of words recalled accurately: of 5 or of 10

6

STEP 6: DECISION

Domain	Date & time of assessment:		
Symptom number (of 22)			
Symptom severity score (of 132)			
Orientation (of 5)			
Immediate memory	of 15 of 30	of 15 of 30	of 15 of 30
Concentration (of 5)			
Neuro exam	Normal Abnormal	Normal Abnormal	Normal Abnormal
Balance errors (of 30)			
Delayed Recall	of 5 of 10	of 5 of 10	of 5 of 10

Date and time of injury: ____________

If the athlete is known to you prior to their injury, are they different from their usual self?

☐ **Yes** ☐ **No** ☐ **Unsure** ☐ **Not Applicable**

(If different, describe why in the clinical notes section)

Concussion Diagnosed?

☐ **Yes** ☐ **No** ☐ **Unsure** ☐ **Not Applicable**

If re-testing, has the athlete improved?

☐ **Yes** ☐ **No** ☐ **Unsure** ☐ **Not Applicable**

I am a physician or licensed healthcare professional and I have personally administered or supervised the administration of this SCAT5.

Signature: ____________

Name: ____________

Title: ____________

Registration number (if applicable): ____________

Date: ____________

SCORING ON THE SCAT5 SHOULD NOT BE USED AS A STAND-ALONE METHOD TO DIAGNOSE CONCUSSION, MEASURE RECOVERY OR MAKE DECISIONS ABOUT AN ATHLETE'S READINESS TO RETURN TO COMPETITION AFTER CONCUSSION.

APPENDIX F: Vestibular Ocular Motor Screening

Subject Identification: ______________________________

Does athlete wear glasses/contacts: ☐ Yes ☐ No

Are they wearing them: ☐ Yes ☐ No

VOMS Test:	Headache 0-10	Dizziness 0-10	Nausea 0-10	Fogginess 0-10	Comments
Baseline Symptoms					
Smooth Pursuits					
Saccades - Horizontal					
Saccades - Vertical					
Convergence					(Near point in cm): Measure 1:__________ Measure 2:__________ Measure 3:__________
VOR - Horizontal					
VOR - Vertical					
Visual Motion Sensitivity Test					

APPENDIX G: Motion Sickness Assessment Questionnaire

Subject Identification: ______________________________

Motion Sickness Assessment Questionnaire (MSAQ)	**Rate (1-9)**
I felt sick to my stomach	
I felt faint-like	
I felt annoyed/irritated	
I felt sweaty	
I felt queasy	
I felt lightheaded	
I felt drowsy	
I felt clammy/cold sweat	
I felt disoriented	
I felt tired/fatigued	
I felt nauseated	
I felt hot/warm	
I felt dizzy	
I felt like I was spinning	
I felt as if I may vomit	
I felt uneasy	

REFERENCES

REFERENCES

1. Council PA. The Physical Activity Council: Participation Report. 2016; http://physicalactivitycouncil.com/PDFs/current.pdf.

2. Langlois JA, Rutland-Brown W, Wald MM. The Epidemiology and Impact of Traumatic Brain Injury: A Brief Overview. *Journal of Head Trauma Rehabilitation.* 2006;21(5):375-378.

3. O'Connor KL, Baker MM, Dalton SL, Dompier TP, Broglio SP, Kerr ZY. Epidemiology of Sport-Related Concussions in High School Athletes: National Athletic Treatment, Injury and Outcomes Network (NATION), 2011-2012 Through 2013-2014. *Journal of Athletic Training.* 2017;52(3):175-185.

4. Gessel LM, Fields SK, Collins CL, Dick RW, Comstock RD. Concussions among United States High School and Collegiate Athletes. *Journal of Athletic Training.* 2007;42(4):495.

5. Daneshvar DHMA, Nowinski CJAB, McKee ACMD, Cantu RCMD. The Epidemiology of Sport-Related Concussion. *Clinics in Sports Medicine.* 2011;30(1):1-17.

6. Zuckerman SL, Kerr ZY, Yengo-Kahn A, Wasserman E, Covassin T, Solomon GS. Epidemiology of Sports-Related Concussion in NCAA Athletes From 2009-2010 to 2013-2014: Incidence, Recurrence, and Mechanisms. *American Journal of Sports Medicine.* 2015;43(11):2654-2662.

7. Covassin T, Swanik CB, Sachs ML. Sex Differences and the Incidence of Concussions Among Collegiate Athletes. *Journal of Athletic Training.* 2003;38(3):238.

8. Hootman JM, Dick R, Agel J. Epidemiology of Collegiate Injuries for 15 Sports: Summary and Recommendations for Injury Prevention Initiatives. *Journal of Athletic Training.* 2007;42(2):311.

9. McCrory P, Meeuwisse WH, Dvořák J, et al. 5th International Conference on Concussion in Sport in Berlin. *British Journal of Sports Medicine.* 2017;51(11):837-837.

10. Broglio SP, Cantu RC, Gioia GA, et al. National Athletic Trainers' Association Position Statement: Management of Sport Concussion. *Journal of Athletic Training.* 2014;49(2):245-265.

11. McCrory P, Meeuwisse WH, Aubry M, et al. Consensus Statement on Concussion in Sport: The 4th International Conference on Concussion in Sport Held in Zurich. *British Journal of Sports Medicine.* 2013;47(5):250-258.

12. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute Effects and Recovery Time Following Concussion in Collegiate Football Players: The NCAA Concussion Study. *Journal of American Medical Association.* 2003;290(19):2556-2563.

13. Leddy JJ, Sandhu H, Sodhi V, Baker JG, Willer B. Rehabilitation of Concussion and Post-concussion Syndrome. *Sports Health: A Multidisciplinary Approach.* 2012;4(2):147-154.

14. Willer B, Leddy JJ. Management of Concussion and Post-Concussion Syndrome. *Current Treatment Options in Neurology.* 2006;8(5):415-426.

15. Meehan WP, d'Hemecourt P, Collins CL, Taylor AM, Comstock RD. Computerized Neurocognitive Testing for the Management of Sport-Related Concussions. *Pediatrics.* 2012;129(1):38-44.

16. Aubry M. Summary and Agreement Statement of the First International Conference on Concussion in Sport, Vienna. *British Journal of Sports Medicine.* 2002;36(1):6-7.

17. Bruce JM, Echemendia RJ. History of Multiple Self-Reported Concussion is not Associated with Reduced Cognitive Abilities. *Neurosurgery.* 2009;64(1):100-106.

18. Echemendia RJ, Putukian M, Mackin RS, Julian L, Shoss N. Neuropsychological Test Performance Prior To and Following Sports-Related Mild Traumatic Brain Injury. *Clinical Journal of Sport Medicine.* 2001;11(1):23-31.

19. Grindel SH, Lovell MR, Collins MW. The Assessment of Sport-Related Concussion: The Evidence Behind Neuropsychological Testing and Management. *Clinical Journal of Sport Medicine.* 2001;11(3):134-143.

20. Gottshall K, Drake A, Gray N, McDonald E, Hoffer ME. Objective Vestibular Tests as Outcome Measures in Head Injury Patients. *Laryngoscope.* 2003;113(10):1746-1750.

21. Hoffer ME, Gottshall KR, Moore R, Balough BJ, Wester D. Characterizing and Treating Dizziness after Mild Head Trauma. *Otology & Neurotology.* 2004;25(2):135-138.

22. Hanes DA, McCollum G. Cognitive-Vestibular Interactions: A Review of Patient Difficulties and Possible Mechanisms. *Journal of Vestibular Research-Equilibrium Orientation.* 2006;16(3):75-91.

23. Baloh RW, Kerber KA. *Baloh and Honrubia's Clinical Neurophysiology of the Vestibular System: Contemporary Neurology* 4th ed. US: Oxford University Press; 2011.

24. Guskiewicz KM, Mihalik JP, Shankar V, et al. Measurement of Head Impacts in Collegiate Football Players: Relationship between Head Impact Biomechanics and Acute Clinical Outcome after Aoncussion. *Neurosurgery.* 2007;61(6):1244-1252.

25. Marar M, McIlvain NM, Fields SK, Comstock RD. Epidemiology of Concussions Among United States High School Athletes in 20 Sports. *American Journal of Sports Medicine.* 2012;40(4):747-755.

26. Guskiewicz KMPATC. Balance Assessment in the Management of Sport-Related Concussion. *Clinics in Sports Medicine.* 2011;30(1):89-102.

27. Goble DJ, Manyak KA, Abdenour TE, Rauh MJ, Baweja HS. An Initial Evaluation of the BTrackS Balance Plate and Sports Balance Software for Concussion Diagnosis. *International Journal of Sports Physical Therapy.* 2016;11(2):149.

28. Preece MHW, Horswill MS, Geffen GM. Assessment of Drivers' Ability to Anticipate Traffic Hazards after Traumatic Brain Injury. *Journal of Neurology Neurosurgery and Psychiatry.* 2011;82(4):447-451.

29. Peek-Asa C, Yang J, Ramirez M, Hamann C, Cheng G. Factors Affecting Hospital Charges and Length of Stay from Teenage Motor Vehicle Crash-Related Hospitalizations among United States Teenagers, 2002–2007. *Accident Analysis and Prevention.* 2011;43(3):595-600.

30. (IIHS) IIfHS. Fatality Facts: Teenagers 2015. 2017; https://www.iihs.org/iihs/topics/t/teenagers/fatalityfacts/teenagers. Accessed September 10, 2018.

31. Administration NHS. Risky Driving. 2017; https://www.nhtsa.gov/. Accessed September 10, 2018.

32. Centre SIR. Sex Differences in Driving and Insurance Risk. 2004; http://www.sirc.org/publik/driving.pdf. Accessed September 10, 2018.

33. Simon F, Corbett C. Road Traffic Offending, Stress, Age, and Accident History among Male and Female Drivers. *Erognomics.* 1996;39(5):757-780.

34. Foss RDPD, Williams AFPD. Adolescent Drivers: Fine-Tuning Our Understanding. *Journal of Adolescent Health.* 2015;57(1):S1-S5.

35. Garner AA, Miller MM, Field J, Noe O, Smith Z, Beebe DW. Impact of Experimentally Manipulated Sleep on Adolescent Simulated Driving. *Sleep Medicine.* 2015;16(6):796-799.

36. Stolwyk RJ, Charlton JL, Ross PE, et al. Characterizing On-Road Driving Performance in Individuals with Traumatic Brain Injury who Pass or Fail an On-Road Driving Assessment. *Disability and Rehabilitation.* 2018:1-8.

37. Reger MA, Welsh RK, Watson GS, Cholerton B, Baker LD, Craft S. The Relationship Between Neuropsychological Functioning and Driving Ability in Dementia: A Meta-Analysis. *Neuropsychology.* 2004;18(1):85-93.

38. Grace J, Amick MM, D'Abreu A, Festa EK, Heindel WC, Ott BR. Neuropsychological Deficits Associated with Driving Performance in Parkinson's and Alzheimer's Disease. *Journal of the International Neuropsychological Society.* 2005;11(6):766-775.

39. Uc EY, Rizzo M, Johnson AM, Dastrup E, Anderson SW, Dawson JD. Road Safety in Drivers with Parkinson disease. *Neurology.* 2009;73(24):2112-2119.

40. Devos H, Brijs T, Alders G, Wets G, Feys P. Driving Performance in Persons with Mild to Moderate Symptoms of Multiple Sclerosis. *Disability and Rehabilitation.* 2013;35(16):1387-1393.

41. Schmidt JD, Hoffman NL, Ranchet M, et al. Driving after Concussion: Is It Safe To Drive after Symptoms Resolve? *Journal of Neurotrauma.* 2017;34(8):1571-1578.

42. Schultheis MTP, Ang JBS, Blake TBS, et al. Driving and Post-Concussion Changes in Neuropsychological Performance. *Physical Medicine and Rehabilitation.* 2012;4(10):S182-S182.

43. Preece MHW, Geffen GM, Horswill MS. Return-to-Driving Expectations Following Mild Traumatic Brain Injury. *Brain Injury.* 2013;27(1):83-91.

44. Safety IIfH. First Few Months of Driving Unsupervised are most Hazardous. 2001; https://www.iihs.org/iihs/sr/statusreport/article/36/2/1. Accessed September 10, 2018.

45. Kirkwood MW, Yeates KO, Wilson PE. Pediatric Sport-Related Concussion: A Review of the Clinical Management of an Oft-Neglected Population. *Pediatrics.* 2006;117(4):1359-1371.

46. Johnson SBPDMPH, Blum RWMDPD, Giedd JNMD. Adolescent Maturity and the Brain: The Promise and Pitfalls of Neuroscience Research in Adolescent Health Policy. *Journal of Adolescent Health.* 2009;45(3):216-221.

47. Mirman JHPD, Albert DPD, Jacobsohn LSPD, Winston FKMDPD. Factors Associated With Adolescents' Propensity to Drive With Multiple Passengers and to Engage in Risky Driving Behaviors. *Journal of Adolescent Health.* 2012;50(6):634-640.

48. Anstey KJ, Wood J, Lord S, Walker JG. Cognitive, Sensory and Physical Factors Enabling Driving Safety in Older Adults. *Clinical Psychology Review.* 2005;25(1):45-65.

49. Schmidt JD, Lynall RC, Lempke LB, Weber ML, Devos H. Post-Concussion Driving Behaviors and Opinions: A Survey of Collegiate Student-Athletes. *Journal of Neurotrauma.* 2018.

50. Henry LC, Elbin RJ, Collins MW, Marchetti G, Kontos AP. Examining Recovery Trajectories after Sport-Related Concussion With a Multimodal Clinical Assessment Approach. *Neurosurgery.* 2016;78(2):232-241.

51. Fazio VC, Lovell MR, Pardini JE, Collins MW. The Relation between Post Concussion Symptoms and Neurocognitive Performance in Concussed Athletes. *Neurorehabilitation.* 2007;22(3):207-216.

52. McCrea M, Guskiewicz K, Randolph C, et al. Incidence, Clinical Course, and Predictors of Prolonged Recovery Time Following Sport-Related Concussion in High School and College Athletes. *Journal of the International Neuropsychological Society.* 2013;19(1):22-33.

53. Prichep LS, McCrea M, Barr W, Powell M, Chabot RJ. Time Course of Clinical and Electrophysiological Recovery After Sport-Related Concussion. *Journal of Head Trauma Rehabilitation.* 2013;28(4):266-273.

54. Lau BC, Collins MW, Lovell MR. Cutoff Scores in Neurocognitive Testing and Symptom Clusters That Predict Protracted Recovery From Concussions in High School Athletes. *Neurosurgery.* 2012;70(2):371-379.

55. Meehan WPMD, Mannix RCMDMPH, Stracciolini AMD, Elbin RJP, Collins MWP. Symptom Severity Predicts Prolonged Recovery after Sport-Related Concussion, but Age and Amnesia Do Not. *Journal of Pediatrics.* 2013;163(3):721-725.

56. Broglio SP, Puetz TW. The Effect of Sport Concussion on Neurocognitive Function, Self-Report Symptoms and Postural Control: A Meta-Analysis. In*.* Vol 38. Cham: Adis International; 2008:53-67.

57. Pearce KL, Sufrinko A, Lau BC, Henry L, Collins MW, Kontos AP. Near Point of Convergence After a Sport-Related Concussion: Measurement Reliability and Relationship to Neurocognitive Impairment and Symptoms. *American Journal of Sports Medicine.* 2015;43(12):3055-3061.

58. Ropper AH, Gorson KC. Clinical Practice: Concussion. *New England Journal of Medicine* 2007;356(2):166.

59. Meehan WP, III, Bachur RG. Sport-Related Concussion. *Pediatrics.* 2009;123(1):114-123.

60. Giza CC, Kutcher JS, Ashwal S, et al. Summary of Evidence-Based Guideline Update: Evaluation and Management of Concussion in Sports: Report of the Guideline Development Subcommittee of the American Academy of Neurology. *Neurology.* 2013;80(24):2250-2257.

61. Steenerson KMD, Starling AJMD. Pathophysiology of Sports-Related Concussion. *Neurologic Clinics.* 2017;35(3):403-408.

62. Gonzalez PGMD, Walker MTMD. Imaging Modalities in Mild Traumatic Brain Injury and Sports Concussion. *Physical Medicine and Rehabilitation.* 2011;3(10):S413-S424.

63. Vagnozzi R, Signoretti S, Cristofori L, et al. Assessment of Metabolic Brain Damage and Recovery following Mild Traumatic Brain Injury: A Multicentre, Proton Magnetic Resonance Spectroscopic Study in Concussed Patients. *Brain.* 2010;133(11):3232-3242.

64. Vagnozzi R, Signoretti S, Tavazzi B, et al. Temporal Window of Metabolic Brain Vulunerability to Concussion: A Pilot 1H-Magnetic Resonance Spectroscopic Study in Concussed Athletes - Part III. *Neurosurgery.* 2008;62(6):1286-1296.

65. Unden J, Romner B. Can Low Serum Levels of S100B Predict Normal CT Findings After Minor Head Injury in Adults?: An Evidence-Based Review and Meta-Analysis. *Journal of Head Trauma Rehabilitation.* 2010;25(4):228-240.

66. Greenwald RM, Gwin JT, Chu JJ, Crisco JJ. Head Impact Severity Measures for Evaluating Mild Traumatic Brain Injury Risk Exposure. *Neurosurgery.* 2008;62(4):789-798.

67. Broglio SP, Schnebel B, Sosnoff JJ, et al. Biomechanical Properties of Concussions in High School Football. *Medicine and Science in Sports and Exercise.* 2010;42(11):2064-2071.

68. Dashnaw ML, Petraglia AL, Bailes JE. An Overview of the Basic Science of Concussion and Subconcussion: Where we are and Where we are going. *Neurosurgical Focus.* 2012;33(6):E5: 1.

69. Len TK, Neary JP, Asmundson GJG, Goodman DG, Bjornson B, Bhambhani YN. Cerebrovascular Reactivity Impairment after Sport-Induced Concussion. *Medicine and Science in Sports and Exercise.* 2011;43(12):2241-2248.

70. Giza CC, Hovda DA. The Neurometabolic Cascade of Concussion. *Journal of Athletic Training.* 2001;36(3):228-235.

71. Kawamata T, Katayama Y, Hovda DA, Yoshino A, Becker DP. Administration of Excitatory Amino Acid Antagonists via Microdialysis Attenuates the Increase in Glucose Utilization Seen Following Concussive Brain Injury. *Journal of Cerebral Blood Flow & Metabolism.* 1992;12(1):12-24.

72. Verweij BH, Amelink GJ, Muizelaar JP. Current Concepts of Cerebral Oxygen Transport and Energy Metabolism after Severe Traumatic Brain Injury. In: Vol 161. Amsterdam: Elsevier Science & Technology; 2007:111-124.

73. Meier TB, Bellgowan PSF, Singh R, Kuplicki R, Polanski DW, Mayer AR. Recovery of Cerebral Blood Flow Following Sports-Related Concussion. *Journal of American Medicial Assosication Neurology.* 2015;72(5):530-538.

74. Wang Y, Nelson LD, LaRoche AA, et al. Cerebral Blood Flow Alterations in Acute Sport-Related Concussion. *Journal of Neurotrauma.* 2016;33(13):1227-1236.

75. Shitaka Y, Tran HT, Bennett RE, et al. Repetitive Closed-Skull Traumatic Brain Injury in Mice Causes Persistent Multifocal Axonal Injury and Microglial Reactivity. *Journal of Neuropathology and Experimental Neurology.* 2011;70(7):551-567.

76. Thompson HJ, Lifshitz J, Marklund N, et al. Lateral Fluid Percussion Brain Injury: A 15-Year Review and Evaluation. *Journal of Neurotrauma.* 2005;22(1):42-75.

77. Giza CC, DiFiori JP. Pathophysiology of Sports-Related Concussion: An Update on Basic Science and Translational Research. *Sports Health: A Multidisciplinary Approach.* 2011;3(1):46-51.

78. Rechel JA, Yard EE, Comstock RD. An Epidemiologic Comparison of High School Sports Injuries Sustained in Practice and Competition. *Journal of Athletic Training.* 2008;43(2):197-204.

79. Rosenthal JA, Foraker RE, Collins CL, Comstock RD. National High School Athlete Concussion Rates From 2005-2006 to 2011-2012. *American Journal of Sports Medicine.* 2014;42(7):1710-1715.

80. Lincoln AE, Caswell SV, Almquist JL, Dunn RE, Norris JB, Hinton RY. Trends in Concussion Incidence in High School Sports: A Prospective 11-Year Study. *American Journal of Sports Medicine.* 2011;39(5):958-963.

81. Lovell MP. The Neurophysiology and Assessment of Sports-Related Head Injuries. *Physical Medicine and Rehabilitation Clinics of North America.* 2009;20(1):39-53.

82. Associations NFoSHS. NFHS Handbook 2015–16. In: Associations NFoSHS, ed. Indianapolis, IN2016.

83. Medicine Io. Sports-Related Concussions in Youth. In: Washington, DC2013.

84. Castile L, Collins CL, McIlvain NM, Comstock RD. The Epidemiology of New Versus Recurrent Sports Concussions among High School Athletes, 2005-2010. *British Journal of Sports Medicine.* 2012;46(8):603-610.

85. Schallmo MS, Weiner JA, Hsu WK. Sport and Sex-Specific Reporting Trends in the Epidemiology of Concussions Sustained by High School Athletes. *Journal of Bone and Joint Surgery.* 2017;99(15):1314-1320.

86. Guskiewicz KM, McCrea M, Marshall SW, et al. Cumulative Effects Associated With Recurrent Concussion in Collegiate Football Players: The NCAA Concussion Study. *Journal of American Medical Association.* 2003;290(19):2549-2555.

87. Dompier TP, Kerr ZY, Marshall SW, et al. Incidence of Concussion During Practice and Games in Youth, High School, and Collegiate American Football Players. *JAMA Pediatrics.* 2015;169(7):659-665.

88. Wasserman EB, Kerr ZY, Zuckerman SL, Covassin T. Epidemiology of Sports-Related Concussions in National Collegiate Athletic Association Athletes From 2009-2010 to 2013-2014: Symptom Prevalence, Symptom Resolution Time, and Return-to-Play Time. *American Journal of Sports Medicine.* 2016;44(1):226-233.

89. Covassin T, Moran R, Elbin RJ. Sex Differences in Reported Concussion Injury Rates and Time Loss From Participation: An Update of the National Collegiate Athletic Association Injury Surveillance Program From 2004-2005 Through 2008-2009. *Journal of Athletic Training.* 2016;51(3):189-194.

90. Guskiewicz KM, Weaver NL, Padua DA, William E. Garrett, Jr. Epidemiology of Concussion in Collegiate and High School Football Players. *American Journal of Sports Medicine.* 2000;28(5):643-650.

91. Houck Z, Asken B, Bauer R, Pothast J, Michaudet C, Clugston J. Epidemiology of Sport-Related Concussion in an NCAA Division I Football Bowl Subdivision Sample. *American Journal of Sports Medicine.* 2016;44(9):2269-2275.

92. Meehan WP, d'Hemecourt P, Dawn Comstock R. High School Concussions in the 2008-2009 Academic Year: Mechanism, Symptoms, and Management. *American Journal of Sports Medicine.* 2010;38(12):2405-2409.

93. Associations TNFoSHS. 2017-18 High School Athletics Participation Survey. 2018; http://www.nfhs.org/ParticipationStatistics/PDF/2017-18%20High%20School%20Athletics%20Participation%20Survey.pdf. Accessed October 15, 2018.

94. Schwarb AW. Number of NCAA College Athletes Reaches All-Time High. 2018; http://www.ncaa.org/about/resources/media-center/news/number-ncaa-college-athletes-reaches-all-time-high. Accessed October 15 2018.

95. Committee IO. *Women in the Olympic Movement* Lausanne, Switzerland: IOC; 2014.

96. Wallace J, Covassin T, Beidler E. Sex Differences in High School Athletes' Knowledge of Sport-Related Concussion Symptoms and Reporting Behaviors. *Journal of Athletic Training.* 2017;52(7):682-688.

97. Zuckerman SL, Yengo-Kahn AM, Buckley TA, Solomon GS, Sills AK, Kerr ZY. Predictors of Postconcussion Syndrome in Collegiate Student-Athletes. *Neurosurgical Focus.* 2016;40(4):E13.

98. Covassin T, Elbin RJ, Bleecker A, Lipchik A, Kontos AP. Are There Differences in Neurocognitive Function and Symptoms Between Male and Female Soccer Players After Concussions? *American Journal of Sports Medicine.* 2013;41(12):2890-2895.

99. Baker JG, Leddy JJ, Darling SR, Shucard J, Makdissi M, Willer BS. Gender Differences in Recovery From Sports-Related Concussion in Adolescents. *Clinical Pediatrics.* 2016;55(8):771-775.

100. Berz K, Divine J, Foss KB, Heyl R, Ford KR, Myer GD. Sex-Specific Differences in the Severity of Symptoms and Recovery Rate following Sports-Related Concussion in Young Athletes. *Physician and Sports Medicine.* 2013;41(2):58-63.

101. Broshek DK, Kaushik T, Freeman JR, Erlanger D, Webbe F, Barth JT. Sex Differences in Outcome following Sports-Related Concussion. *Journal of Neurosurgery.* 2005;102(5):856-863.

102. Schneider KJ, Emery CA, Kang JA, Schneider GM, Meeuwisse WH. Examining Sport Concussion Assessment Tool Ratings for Male and Female Youth Hockey Players with and without a History of Concussion. *British Journal of Sports Medicine.* 2010;44(15):1112-1117.

103. Covassin T, Elbin RJ, Harris W, Parker T, Kontos A. The Role of Age and Sex in Symptoms, Neurocognitive Performance, and Postural Stability in Athletes After Concussion. *American Journal of Sports Medicine.* 2012;40(6):1303-1312.

104. Chin EY, Nelson LD, Barr WB, McCrory P, McCrea MA. Reliability and Validity of the Sport Concussion Assessment Tool–3 (SCAT3) in High School and Collegiate Athletes. *American Journal of Sports Medicine.* 2016;44(9):2276-2285.

105. Kostyun RO, Hafeez I. Protracted Recovery From a Concussion: A Focus on Gender and Treatment Interventions in an Adolescent Population. *Sports Health: A Multidisciplinary Approach.* 2015;7(1):52-57.

106. Frommer LJ, Gurka KK, Cross KM, Ingersoll CD, Comstock RD, Saliba SA. Sex Differences in Concussion Symptoms of High School Athletes. *Journal of Athletic Training.* 2011;46(1):76-84.

107. Brown DA, Elsass JA, Miller AJ, Reed LE, Reneker JC. Differences in Symptom Reporting Between Males and Females at Baseline and After a Sports-Related Concussion: A Systematic Review and Meta-Analysis. *Sports Medicine.* 2015;45(7):1027-1040.

108. Ono KE, Burns TG, Bearden DJ, McManus SM, King H, Reisner A. Sex-Based Differences as a Predictor of Recovery Trajectories in Young Athletes After a Sports-Related Concussion. *American Journal of Sports Medicine.* 2016;44(3):748-752.

109. Leddy JJMD, Baker JGP, Willer BP. Active Rehabilitation of Concussion and Post-concussion Syndrome. *Physical Medicine and Rehabilitation Clinics of North America.* 2016;27(2):437-454.

110. Lau BC, Collins MW, Lovell MR. Sensitivity and Specificity of Subacute Computerized Neurocognitive Testing and Symptom Evaluation in Predicting Outcomes After Sports-Related Concussion. *American Journal of Sports Medicine.* 2011;39(6):1209-1216.

111. Colvin AC, Mullen J, Lovell MR, West RV, Collins MW, Groh M. The Role of Concussion History and Gender in Recovery From Soccer-Related Concussion. *American Journal of Sports Medicine.* 2009;37(9):1699-1704.

112. Ponsford J, Cameron P, Fitzgerald M, Grant M, Mikocka-Walus A, Schonberger M. Predictors of Postconcussive Symptoms 3 Months After Mild Traumatic Brain Injury. *Neuropsychology.* 2012;26(3):304-313.

113. Kontos AP, Reches A, Elbin RJ, et al. Preliminary Evidence of Reduced Brain Network Activation in Patients with Post-Traumatic Migraine following Concussion. *Brain Imaging and Behavior.* 2016;10(2):594-603.

114. McCrea M, Prichep L, Powell MR, Chabot R, Barr WB. Acute Effects and Recovery After Sport-Related Concussion: A Neurocognitive and Quantitative Brain Electrical Activity Study. *Journal of Head Trauma Rehabilitation.* 2010;25(4):283-292.

115. Sufrinko AM, Mucha A, Covassin T, et al. Sex Differences in Vestibular/Ocular and Neurocognitive Outcomes After Sport-Related Concussion. *Clinical Journal of Sport Medicine.* 2017;27(2):133-138.

116. Zuckerman SL, Solomon GS, Forbes JA, Haase RF, Sills AK, Lovell MR. Response to Acute Concussive Injury in Soccer Players: Is Gender a Modifying Factor? *Journal of Neurosurgery-Pediatrics.* 2012;10(6):504-510.

117. Kerr ZY, Register-Mihalik JK, Kroshus E, Baugh CM, Marshall SW. Motivations Associated With Nondisclosure of Self-Reported Concussions in Former Collegiate Athletes. *American Journal of Sports Medicine.* 2016;44(1):220-225.

118. Zuckerman SL, Wasserman E, Yengo-Kahn AM, Solomon G, Kerr Z. Descriptive Epidemiology, Mechanisms, and Symptom Resolution of Concussion Sustained by National Collegiate Athletic Association Student Athletes, 2009/10 to 2013/14 Academic Years. *Neurosurgery.* 2015;62:223-224.

119. Valovich McLeod TC, Hale TD. Vestibular and Balance Issues following Sport-Related Concussion. *Brain Injury.* 2015;29(2):175-184.

120. Benedict PA, Baner NV, Harrold GK, et al. Gender and Age Predict Outcomes of Cognitive, Balance and Vision Testing in a Multidisciplinary Concussion Center. *Journal of the Neurological Sciences.* 2015;353(1):111-115.

121. Tierney RT, Sitler MR, Swanik CB, Swanik KA, Higgins M, Torg J. Gender Differences in Head-Neck Segment Dynamic Stabilization during Head Acceleration. *Medicine and Science in Sports and Exercise.* 2005;37(2):272-279.

122. Emerson CS, Headrick JP, Vink R. Estrogen Improves Biochemical and Neurologic Outcome following Traumatic Brain Injury in Male Rats, but not in Females. *Brain Research.* 1993;608(1):95-100.

123. Covassin TPATC, Elbin RJP. The Female Athlete: The Role of Gender in the Assessment and Management of Sport-Related Concussion. *Clinics in Sports Medicine.* 2011;30(1):125-131.

124. Tierney RT, Higgins M, Caswell SV, et al. Sex Differences in Head Acceleration During Heading While Wearing Soccer Headgear. *Journal of Athletic Training.* 2008;43(6):578-584.

125. Lovely JM, Dodge TM, Guyer MS, Mullin E. Differences in Relative Neck Strength and Time to Peak Torque Among Male and Female Division III Soccer Athletes. *Journal of Athletic Training.* 2017;52(6):S210.

126. Kerr ZY, Register-Mihalik JK, Marshall SW, Evenson KR, Mihalik JP, Guskiewicz KM. Disclosure and Non-Disclosure of Concussion and Concussion Symptoms in Athletes: Review and Application of the Socio-Ecological Framework. *Brain Injury.* 2014;28(8):1009-1021.

127. Register-Mihalik JK, Guskiewicz KM, McLeod TCV, Linnan LA, Mueller FO, Marshall SW. Knowledge, Attitude, and Concussion-Reporting Behaviors Among High School Athletes: A Preliminary Study. *Journal of Athletic Training.* 2013;48(5):645-653.

128. Broglio SP, Macciocchi SN, Ferrara MS. Sensitivity of the Concussion Assessment Battery. *Neurosurgery.* 2007;60(6):1050-1057.

129. Downey RI, Hutchison MG, Comper P. Determining Sensitivity and Specificity of the Sport Concussion Assessment Tool 3 (SCAT3) Components in University Athletes. *Brain Injury.* 2018;32(11):1345-1352.

130. Lovell MR, Collins MW. Neuropsychological Assessment of the College Football Player. *Journal of Head Trauma Rehabilitation.* 1998;13(2):9-26.

131. Piland SG, Motl RW, Ferrara MS, Peterson CL. Evidence for the Factorial and Construct Validity of a Self-Report Concussion Symptoms Scale. *Journal of Athletic Training.* 2003;38(2):104-112.

132. Randolph C, Millis S, Barr WB, et al. Concussion Symptom Inventory: An Empirically Derived Scale for Monitoring Resolution of Symptoms Following Sport-Related Concussion. *Archives of Clinical Neuropsychology.* 2009;24(3):219-229.

133. Ellemberg D, Henry LC, Macciocchi SN, Guskiewicz KM, Broglio SP. Advances in Sport Concussion Assessment: From Behavioral to Brain Imaging Measures. *Journal of Neurotrauma.* 2009;26(12):2365-2382.

134. Valovich McLeod TC, Bay RC, Lam KC, Chhabra A. Representative Baseline Values on the Sport Concussion Assessment Tool 2 (SCAT2) in Adolescent Athletes Vary by Gender, Grade, and Concussion History. *American Journal of Sports Medicine.* 2012;40(4):927-933.

135. Shehata N, Wiley JP, Richea S, Benson BW, Duits L, Meeuwisse WH. Sport Concussion Assessment Tool: Baseline Values for Varsity Collision Sport Athletes. *British Journal of Sports Medicine.* 2009;43(10):730-734.

136. Mailer BJ, McLeod TCV, Bay RC. Healthy Youth are Reliable in Reporting Symptoms on a Graded Symptom Scale. *Journal of Sport Rehabilitation.* 2008;17(1):11-20.

137. Kontos AP, Collins M, Russo SA. An Introduction to Sports Concussion for the Sport Psychology Consultant. *Journal of Applied Sport Psychology.* 2004;16(3):220-235.

138. Teasdale G, and Jennett, D. Assessment of Coma: Assessment of Coma and Impaired Consciousness. *Injury.* 1974;6(3):265-265.

139. Makdissi M, Darby D, Maruff P, Ugoni A, Brukner P, McCrory PR. Natural History of Concussion in Sport: Markers of Severity and Implications for Management. *American Journal of Sports Medicine.* 2010;38(3):464-471.

140. Erlanger D, Kaushik T, Cantu R, et al. Symptom-Based Assessment of the Severity of a Concussion. *Journal of Neurosurgery.* 2003;98(3):477-484.

141. Lovell MR, Iverson GL, Collins MW, et al. Measurement of Symptoms Following Sports-Related Concussion: Reliability and Normative Data for the Post-Concussion Scale. *Applied Neuropsychology.* 2006;13(3):166-174.

142. Collins MW, Iverson GL, Lovell MR, McKeag DB, Norwig J, Maroon J. On-Field Predictors of Neuropsychological and Symptom Deficit Following Sports-Related Concussion. *Clinical Journal of Sport Medicine.* 2003;13(4):222-229.

143. McCrea M, Barr WB, Guskiewicz K, et al. Standard Regression-Based Methods for Measuring Recovery after Sport-Related Concussion. *Journal of the International Neuropsychological Society.* 2005;11(1):58-69.

144. Mansell JL, Tierney RT, Higgins M, McDevitt J, Toone N, Glutting J. Concussive Signs and Symptoms following Head Impacts in Collegiate Athletes. *Brain Injury.* 2010;24(9):1070-1074.

145. Iverson GL, Gaetz M, Lovell MR, Collins MW. Cumulative Effects of Concussion in Amateur Athletes. *Brain Injury.* 2004;18(5):433-443.

146. Korngold C, Farrell HM, Fozdar M. The National Football League and Chronic Traumatic Encephalopathy: Legal Implications. *Journal of the American Academy of Psychiatry and the Law Online.* 2013;41(3):430-436.

147. Kroshus E, Garnett B, Hawrilenko M, Baugh CM, Calzo JP. Concussion Under-Reporting and Pressure from Coaches, Teammates, Fans, and Parents. *Social Science & Medicine.* 2015;134:66-75.

148. Collie A, Darby D, Maruff P. Computerised Cognitive Assessment of Athletes with Sports Related Head Injury. *British Journal of Sports Medicine.* 2001;35(5):297-302.

149. Rahman-Filipiak AAM, Woodard JL. Administration and Environment Considerations in Computer-Based Sports-Concussion Assessment. *Neuropsychology Review.* 2013;23(4):314-334.

150. Schatz P, Pardini JE, Lovell MR, Collins MW, Podell K. Sensitivity and Specificity of the ImPACT Test Battery for Concussion in Ahletes. *Archives of Clinical Neuropsychology.* 2006;21(1):91-99.

151. Lichtenstein JD, Moser RS, Schatz P. Age and Test Setting Affect the Prevalence of Invalid Baseline Scores on Neurocognitive Tests. *American Journal of Sports Medicine.* 2014;42(2):479-484.

152. Moser RS, Schatz P, Neidzwski K, Ott SD. Group Versus Individual Administration Affects Baseline Neurocognitive Test Performance. *American Journal of Sports Medicine.* 2011;39(11):2325-2330.

153. Moser RS, Schatz P, Lichtenstein JD. The Importance of Proper Administration and Interpretation of Neuropsychological Baseline and Postconcussion Computerized Testing. *Applied Neuropsychology: Child.* 2015;4(1):41-48.

154. Guskiewicz KM, Bruce SL, Cantu RC, et al. National Athletic Trainers' Association Position Statement: Management of Sport-Related Concussion. *Journal of Athletic Training.* 2004;39(3):280-297.

155. Collins MW, Grindel SH, Lovell MR, et al. Relationship Between Concussion and Neuropsychological Performance in College Football Players. *Journal of American Medical Association.* 1999;282(10):964-970.

156. Iverson GL, Brooks BL, Collins MW, Lovell MR. Tracking Neuropsychological Recovery following Concussion in Sport. *Brain Injury.* 2006;20(3):245-252.

157. Randolph C, McCrea M, Barr WB. Is Neuropsychological Testing Useful in the Management of Sport-Related Concussion? *Journal of Athletic Training.* 2005;40(3):139-152.

158. Echemendia RJ, Iverson GL, McCrea M, et al. Advances in Neuropsychological Assessment of Sport-Related Concussion. *British Journal of Sports Medicine.* 2013;47(5):294-298.

159. Barr WB, McCrea M. Sensitivity and Specificity of Standardized Neurocognitive Testing Immediately following Sports Concussion. *Journal of the International Neuropsychological Society.* 2001;7(6):693-702.

160. Belanger HG, Vanderploeg RD. The Neuropsychological Impact of Sports-Related Concussion: A Meta-Analysis. *Journal of the International Neuropsychological Society.* 2005;11(4):345-357.

161. Iverson GL, Lovell MR, Collins MW. Interpreting Change on ImPACT following Sport Concussion. *Clinical Neuropsychologist* 2003;17(4):460-467.

162. Catena RD, van Donkelaar P, Chou L-S. Cognitive Task Effects on Gait Stability following Concussion. *Experimental Brain Research.* 2007;176(1):23-31.

163. Parker TM, Osternig LR, Van Donkelaar P, Chou LS. Gait Stability following Concussion. *Medicine and Science in Sports and Exercise.* 2006;38(6):1032-1040.

164. Guskiewicz KM, Riemann BL, Perrin DH, Nashner LM. Alternative Approaches to the Assessment of Mild Head Injury in Athletes. *Medicine and Science in Sports and Exercise.* 1997;29(7):S213-S221.

165. Peterson CL, Ferrara MS, Mrazik M, Piland T, Elliott T. Evaluation of Neuropsychological Stability following Cerebral Domain Scores and Postural Concussion in Sports. *Clinical Journal of Sport Medicine.* 2003;13(4):230-237.

166. Guskiewicz KM, Ross SE, Marshall SW. Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes. *Journal of Athletic Training.* 2001;36(3):263.

167. Eileen De Monte V, Malke Geffen G, Randall May C, McFarland K, Heath P, Neralic M. The Acute Effects of Mild Traumatic Brain Injury on Finger Tapping With and Without

Word Repetition. *Journal of Clinical and Experimental Neuropsychology.* 2005;27(2):224-239.

168. Buckley TA, Burdette G, Kelly K. Concussion-Management Practice Patterns of National Collegiate Athletic Association Division II and III Athletic Trainers: How the Other Half Lives. *Journal of Athletic Training.* 2015;50(8):879-888.

169. Mucha A, Collins MW, Elbin RJ, et al. A Brief Vestibular/Ocular Motor Screening (VOMS) Assessment to Evaluate Concussions: Preliminary Findings. *American Journal of Sports Medicine.* 2014;42(10):2479-2486.

170. Ellis MJ, Cordingley D, Vis S, Reimer K, Leiter J, Russell K. Vestibulo-Ocular Dysfunction in Pediatric Sports-Related Concussion. *Journal of Neurosurgery-Pediatrics.* 2015;16(3):248-255.

171. Corwin DJMD, Wiebe DJP, Zonfrillo MRMDM, et al. Vestibular Deficits following Youth Concussion. *Journal of Pediatrics.* 2015;166(5):1221-1225.

172. Galetta KM, Brandes LE, Maki K, et al. The King–Devick Test and Sports-Related Concussion: Study of a Rapid Visual Screening Tool in a Collegiate Cohort. *Journal of the Neurological Sciences.* 2011;309(1):34-39.

173. Kontos AP, Sufrinko A, Elbin RJ, Puskar A, Collins MW. Reliability and Associated Risk Factors for Performance on the Vestibular/Ocular Motor Screening (VOMS) Tool in Healthy Collegiate Athletes. *American Journal of Sports Medicine.* 2016;44(6):1400-1406.

174. Naguib MB, Madian Y, Refaat M, Mohsen O, El Tabakh M, Abo-Setta A. Characterisation and Objective Monitoring of Balance Disorders following Head Trauma, using Videonystagmography. *Journal of Laryngology and Otology.* 2012;126(1):26-33.

175. Kontos AP, Elbin RJ, Schatz P, et al. A Revised Factor Structure for the Post-Concussion Symptom Scale: Baseline and Postconcussion Factors. *American Journal of Sports Medicine.* 2012;40(10):2375-2384.

176. Lau BC, Kontos AP, Collins MW, Mucha A, Lovell MR. Which On-field Signs/Symptoms Predict Protracted Recovery From Sport-Related Concussion Among High School Football Players? *American Journal of Sports Medicine.* 2011;39(11):2311-2318.

177. Cullen KE. The Vestibular System: Multimodal Integration and Encoding of Self-Motion for Motor Control. *Trends in Neurosciences.* 2012;35(3):185-196.

178. Khan S, Chang R. Anatomy of the Vestibular System: A Review. *Neurorehabilitation.* 2013;32(3):437-443.

179. Allum JHJ. Recovery of Vestibular Ocular Reflex Function and Balance Control after a Unilateral Peripheral Vestibular Deficit. *Frontiers in Neurology.* 2012;3:83.

180. Nashner LM. Adaptation of Human Movement to Altered Environments. In. Vol 5: Elsevier Ltd; 1982:358-361.

181. Shumway-Cook A, Horak FB. Assessing the Influence of Sensory Interaction on Balance: Suggestion from the Field. *Physical Therapy.* 1986;66(10):1548.

182. Murray N, Salvatore A, Powell D, Reed-Jones R. Reliability and Validity Evidence of Multiple Balance Assessments in Athletes With a Concussion. *Journal of Athletic Training.* 2014;49(4):540-549.

183. Slobounov S, Slobounov E, Sebastianelli W, Cao C, Newell K. Differential Rate of Recovery in Athletes after First and Second Concussion Episodes. *Neurosurgery.* 2007;61(2):338-344.

184. Goble DJ, Baweja HS. Normative Data for the BTrackS Balance Test of Postural Sway: Results from 16,357 Community-Dwelling Individuals Who Were 5 to 100 Years Old. *Physical Therapy.* 2018;98(9):779-785.

185. Bell DR, Guskiewicz KM, Clark MA, Padua DA. Systematic Review of the Balance Error Scoring System. *Sports Health: A Multidisciplinary Approach.* 2011;3(3):287-295.

186. Guskiewicz KM. Postural Stability Assessment Following Concussion: One Piece of the Puzzle. *Clinical Journal of Sport Medicine.* 2001;11(3):182-189.

187. Nashner LM, Black FO, Wall Cd. Adaptation to Altered Support and Visual Conditions during Stance: Patients with Vestibular Deficits. *Journal of Neuroscience.* 1982;2(5):536-544.

188. Yorke AM, Smith L, Babcock M, Alsalaheen B. Validity and Reliability of the Vestibular/Ocular Motor Screening and Associations With Common Concussion Screening Tools. *Sports Health: A Multidisciplinary Approach.* 2017;9(2):174-180.

189. Elbin RJ, Sufrinko A, Anderson MN, et al. Prospective Changes in Vestibular and Ocular Motor Impairment After Concussion. *Journal of Neurologic Physical Therapy.* 2018;42(3):142-148.

190. DuPrey KM, Webner D, Lyons A, Kucuk CH, Ellis JT, Cronholm PF. Convergence Insufficiency Identifies Athletes at Risk of Prolonged Recovery From Sport-Related Concussion. *American Journal of Sports Medicine.* 2017;45(10):2388-2393.

191. Bompadre V, Jinguji TM, Yanez ND, et al. Washington State's Lystedt Law in Concussion Documentation in Seattle Public High Schools. *Journal of Athletic Training.* 2014;49(4):486-492.

192. Gregoire C. Youth Sports—Concussion and Head Injury Guidelines—Injured Athlete Restrictions. In. Washington2009.

193. Oliaro S, Anderson S, Hooker D. Management of Cerebral Concussion in Sports: The Athletic Trainer's Perspective. *Journal of Athletic Training.* 2001;36(3):257-262.

194. McLeod TCV, Lewis JH, Whelihan K, Bacon CEW. Rest and Return to Activity After Sport-Related Concussion: A Systematic Review of the Literature. *Journal of Athletic Training.* 2017;52(3):262-287.

195. Alsalaheen BA, Mucha A, Morris LO, et al. Vestibular Rehabilitation for Dizziness and Balance Disorders After Concussion. *Journal of Neurologic Physical Therapy.* 2010;34(2):87-93.

196. Gagnon I, Galli C, Friedman D, Grilli L, Iverson GL. Active Rehabilitation for Children who are Slow to Recover following Sport-Related Concussion. *Brain Injury.* 2009;23(12):956-964.

197. Sady MDP, Vaughan CGP, Gioia GAP. School and the Concussed Youth: Recommendations for Concussion Education and Management. *Physical Medicine and Rehabilitation Clinics of North America.* 2011;22(4):701-719.

198. Master CL, Gioia GA, Leddy JJ, Grady MF. Importance of 'Return-to-Learn' in Pediatric and Adolescent Concussion. *Pediatric Annals.* 2012;41(9):e160-E185.

199. Echemendia RJ, Giza CC, Kutcher JS. Developing Guidelines for Return to Play: Consensus and Evidence-Based Approaches. *Brain Injury.* 2015;29(2):185-194.

200. Thomas DJ, Coxe K, Li H, et al. Length of Recovery From Sports-Related Concussions in Pediatric Patients Treated at Concussion Clinics. *Clinical Journal of Sport Medicine.* 2018;28(1):56-63.

201. O'Neill JA, Cox MK, Clay OJ, et al. A Review of the Literature on Pediatric Concussions and Return-to-Learn (RTL): Implications for RTL Policy, Research, and Practice. *Rehabilitation Psychology.* 2017;62(3):300-323.

202. DiFazio M, Silverberg ND, Kirkwood MW, Bernier R, Iverson GL. Prolonged Activity Restriction After Concussion: Are We Worsening Outcomes? *Clinical Pediatrics.* 2016;55(5):443-451.

203. Schneider KH. Cognitive Rest: An Integrated Literature Review. *Journal of School Nursing.* 2016;32(4):234-240.

204. Stein CJ, MacDougall R, Quatman-Yates CC, et al. Young Athletes' Concerns About Sport-Related Concussion: The Patient's Perspective. *Clinical Journal of Sport Medicine.* 2016;26(5):386-390.

205. Williamson CL, Norte GE, Broshek DK, Hart JM, Resch JE. Return to Learn After Sport-Related Concussion: A Survey of Secondary School and Collegiate Athletic Trainers. *Journal of Athletic Training.* 2018;53(10):990-1003.

206. Iverson GLP, Gioia GAP. Returning to School Following Sport-Related Concussion. *Physical Medicine and Rehabilitation Clinics of North America.* 2016;27(2):429-436.

207. Prevention CfDCa. Years of potential life lost (YPLL) reports, 1999-2015. 2017.

208. O'Brien F, Bible J, Liu D, Simons-Morton BG. Do Young Drivers Become Safer After Being Involved in a Collision? *Psychological Science.* 2017;28(4):407-413.

209. Prevention CfDCa. How is the US Doing? *Overview* 2016; https://www.cdc.gov/vitalsigns/motor-vehicle-safety/index.html.

210. Prevention CfDCa. Teen Drivers: Get the Facts. *Motor Vehicle Safety* 2018; https://www.cdc.gov/motorvehiclesafety/teen_drivers/teendrivers_factsheet.html.

211. (IIHS) IIfHS. Fatality Facts: Teenagers 2016. 2017; http://www.iihs.org/iihs/topics/t/teenagers/fatalityfacts/teenagers.

212. Baker A, Unsworth CA, Lannin NA. Fitness-to-Drive after Mild Traumatic Brain Injury: Mapping the Time Trajectory of Recovery in the Acute Stages Post-Injury. *Accident Analysis and Prevention.* 2015;79:50-55.

213. Preece MHW, Horswill MS, Geffen GM. Driving After Concussion: The Acute Effect of Mild Traumatic Brain Injury on Drivers' Hazard Perception. *Neuropsychology.* 2010;24(4):493-503.

214. Preece MHW, Horswill MS, Ownsworth T. Do Self-Reported Concussions have Cumulative or Enduring Effects on Drivers' Anticipation of Traffic Hazards? *Brain Injury.* 2016;30(9):1096-1102.

215. Stuart EA, Duerson DH, Rodenberg RE, Ravindran R, MacDonald JP. Return to Drive Counseling After Sports-Related Concussion: A Quality Improvement Project. *Pediatric Quality & Safety U6.* 2016;1(2):e006.

216. Klein TAPAFF, Graves JMPMPH, Graham JYAS. Driving After Adolescent Concussion: Advice From Nurse Practitioners in the Absence of Standardized Recommendations. *Journal of Pediatric Health Care.* 2016;31(4):441-451.

217. MacDonald J, Patel N, Young J, Stuart E. Returning Adolescents to Driving after Sports-Related Concussions: What Influences Physician Decision-Making. *Journal of Pediatrics.* 2018;194:177-181.

218. Collia DV, Sharp J, Giesbrecht L. The 2001 National Household Travel Survey: A Look into the Travel Patterns of Older Americans. *Journal of Safety Research.* 2003;34(4):461-470.

219. Marottoli RA, de Leon CFM, Glass TA, Williams CS, Cooney LM, Berkman LF. Consequences of Driving Cessation: Decreased Out-of-Home Activity Levels. *Journals of Gerontology Series B-Psychological Sciences and Social Sciences.* 2000;55(6):S334-S340.

220. Fonda SJ, Wallace RB, Herzog AR. Changes in Driving Patterns and Worsening Depressive Symptoms among Older Adults. *Journals of Gerontology B-Psychological Sciences and Social Sciences.* 2001;56(6):S343-S351.

221. Bieliauskas LA. Neuropsychological Assessment of Geriatric Driving Competence. *Brain Injury.* 2005;19(3):221-226.

222. Lew HL PJ, Lee EH, Huang HC, Jaffe DL, Brodd E. Predictive Validity of Driving Simulator Assessments following TBI. *Brain Injury.* 2005;19(3):177–188.

223. Freund B, Gravenstein S, Ferris R, Shaheen E. Evaluating Driving Performance of Cognitively Impaired and Healthy Older Adults: A Pilot Study Comparing On□Road Testing and Driving Simulation. *Journal of the American Geriatrics Society.* 2002;50(7):1309-1310.

224. Owsley C, Ball K, Sloane ME, Roenker DL. Visual/Cognitive Correlates of Vehicle Accidents in Older Drivers. *Psychology and Aging.* 1991;6(3):403-415.

225. Rosen PN WJ. Driving Assessment in the Clinical Setting: Utility for Testing and Treatment. *Advances in Transportation Studies.* 2004:91-96.

226. Bouchner P. Interactive Driving Simulator - History, Design and their Utilization in area of HMI Research. *International Journal of Systems Applications, Engineering & Development.* 2016;10:179-188.

227. Lee HC, Lee AH, Cameron D. Assessing the Driving Performance of Older Adult Drivers: On-Road Versus Simulated Driving. *Accident Analysis and Prevention.* 2003;35(5):797-803.

228. DRIVE S. Occupational Therapy Driving Simulation. 2018; http://stisimdrive.com/, August 19th, 2018.

229. Echemendia RJ, Meeuwisse W, McCrory P, et al. The Sport Concussion Assessment Tool 5th Edition (SCAT5). *British Journal of Sports Medicine.* 2017:bjsports-2017-097506.

230. McCrea M, Kelly JP, Randolph C, et al. Standardized Assessment of Concussion (SAC): On-Site Mental Status Evaluation of the Athlete. *Journal of Head Trauma Rehabilitation.* 1998;13(2):27-35.

231. Riemann BL, Guskiewicz KM, Shields EW. Relationship between Clinical and Forceplate Measures of Postural Stability. *Journal of Sport Rehabilitation.* 1999;8(2):71-82.

232. ImPACT Applications I. ImPACT Administration and Interpretation Manual. In: Lovell MR, ed: Mark R. Lovell; 2018.

233. Elbin RJ, Schatz P, Covassin T. One-Year Test-Retest Reliability of the Online Version of ImPACT in High School Athletes. *American Journal of Sports Medicine.* 2011;39(11):2319-2324.

234. Alsalaheen B, Stockdale K, Pechumer D, Broglio SP. Validity of the Immediate Post Concussion Assessment and Cognitive Testing (ImPACT). *Sports Medicine.* 2016;46(10):1487-1501.

235. Gianaros PJ, Muth ER, Mordkoff JT, Levine MX, Stern RM. A Questionnaire for the Assessment of the Multiple Dimensions of Motion Sickness. *Aviation Space and Environmental Medicine.* 2001;72(2):115-119.

236. Stern DH. Choosing Full-function Patient Simulators, Creating and Using the Simulation Suite. In: Elsevier Inc; 2007:205-215.

237. Lew HL, Rosen PN, Thomander D, Poole JH. The Potential Utility of Driving Simulators in the Cognitive Rehabilitation of Combat-Returnees With Traumatic Brain Injury. *Journal of Head Trauma Rehabilitation.* 2009;24(1):51-56.

238. Koo TK, Li MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine.* 2016;15(2):155-163.

239. Mukaka MM. Statistics Corner: A guide to appropriate use of Correlation coefficient in medical research. *Malawi Medical Journal.* 2012;24(3):69-71.

240. Rizzo M, McGehee DV, Dawson JD, Anderson SN. Simulated Car Crashes at Intersections in Drivers with Alzheimer Disease. *Alzheimer Disease & Associated Disorders.* 2001;15(1):10-20.

241. Ponds R, Brouwer WH, Vanwolffelaar PC. Age-Differences in Divided Attention in a Simulated Driving Task. *Journals of Gerontology.* 1988;43(6):P151-P156.

242. Cox DJ, Taylor P, Kovatchev B. Driving Simulation Performance Predicts Future Accidents among Older Drivers. *Journal of the American Geriatrics Society.* 1999;47(3):381-382.

243. Brouwer WH, Withaar FK. Fitness to Drive After Traumatic Brain Injury. *Neuropsychological Rehabilitation.* 1997;7(3):177-193.

244. Cullen N, Krakowski A, Taggart C. Early Neuropsychological Tests as Correlates of Return to Driving after Traumatic Brain Injury. *Brain Injury.* 2014;28(1):38-43.

245. Dawson JD, Uc EY, Anderson SW, Johnson AM, Rizzo M. Neuropsychological Predictors of Driving Errors in Older Adults. *Journal of the American Geriatrics Society.* 2010;58(6):1090-1096.